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The Fishery on Antarctic Krill: Defining an Ecosystem Approach to Management

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ABSTRACT: Estimates of the standing stock of Antarctic krill (*Euphausia superba*) have ranged from less than 100 million tons to over a billion tons. While considerable uncertainty is associated with these estimates, the fishery on Antarctic krill has the potential to be among the largest in the world. The harvest of Antarctic krill is currently managed by the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), part of the Antarctic Treaty system. In this review, we examine the political context and management approach of CCAMLR; we review the current understanding of natural controls on population growth of the resource; and we discuss future options for CCAMLR. We conclude that the political foundation for the CCAMLR mandate of an "ecosystem approach to management" is sound; that substantial progress has been made toward interpreting and implementing the Convention; and that environmental factors may exert a substantial influence on krill recruitment and population growth. We also note that the current fishery in the southwest Atlantic sector of the Southern Ocean (ca. 100,000 tons per year) is small compared with the precautionary limit established for this area by CCAMLR (1,500,000 tons per year), but fishing effort concentrated near colonies of land-breeding krill predators may pose a threat; that improvements to the current krill yield model are warranted; and that uncertainty regarding the character of natural variability in krill abundance and regarding the future development of the krill fishery act to obscure a strategic vision for CCAMLR. We discuss the likelihood of future scenarios and the appropriate options for CCAMLR, and we suggest a general outline for the development of a management scheme based on ecosystem process monitoring. We conclude with a comment regarding the value of a conservation ethic in the face of uncertainty.

KEY WORDS: CCAMLR, *Euphausia superba*, precautionary approach to fisheries management.

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I. INTRODUCTION

We are currently at a juncture in the evolution of a management regime for the international fishery on Antarctic krill (*Euphausia superba*). The concept of an ecosystem approach to management, which is incorporated in the terms of reference for the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), has proven difficult to define and implement in terms of operational rules for managing the fishery. In the absence of information regarding demand by krill predators, dispersion and movement of krill throughout their habitat, and variability in recruitment and the factors that influence it, a simple population yield model was adopted in order to establish a precautionary limit to harvesting. The slow development of the fishery has given us time to understand more of the natural history of Antarctic krill, and we are now in a position to consider how this information may be incorporated into an enhanced management scheme.

Early proponents of a fishery on Antarctic krill argued that the resource was large enough to sustain a harvest comparable to the global catch of marine fishes. The potential of the krill harvest to feed the world was not realized, however, for a variety of reasons: (1) estimates of krill abundance and yield were based on gross and sometimes incorrect assumptions regarding predator consumption rates, krill production rates, and a production surplus due to the demise of baleen whales in the Southern Ocean; (2) harvesting, processing, and distributing krill was not economically viable on a large scale; and (3) market demand for krill products did not develop.

CCAMLR came into force in the early 1980s after a decade of krill fishing during which annual harvests approached 500,000 tons. The fishery was large and raised concerns regarding the health of krill predator populations, but the catches never reached the level of early forecasts. CCAMLR established a monitoring program in order to track the status of land-breeding predator populations at selected sites (Agnew, 1997) and began to address the problem of how to assess the krill resource and estimate its yield. In the early 1990s, political and economic changes resulted in a sharp decrease in fishing for krill, and the annual harvest fell to less than 100,000 tons, where it remains to date. In the meantime, CCAMLR adopted a krill yield model and set a precautionary limit for the krill harvest in the southwest Atlantic sector of the Southern Ocean at 1,500,000 tons per year based on a 1981 survey of krill biomass. CCAMLR also set a precautionary limit for krill harvest in the Indian Ocean sector of 775,000 tons per year based on a 1996 survey conducted by the Australian government (Pauly et al., 1996).

More recently, new products derived from krill have been developed and several countries have announced their intentions to enter the krill fishery (Nicol and Endo, 1999). Additional concerns were raised when results from the CCAMLR monitoring program indicated substantial overlap between the geographic distribution of fishing effort and the foraging ranges of land-breeding krill predators. Moreover, the krill resource may not be stable over time. Results of field studies conducted in the South Shetland Islands suggest that the krill population in this area is sustained by occasional strong year classes, that adult reproductive output and pre-recruit survival are affected by physical and biological factors, and that multiyear variations in these factors may lead to long-term fluctuations in krill population levels (Siegel and Loeb, 1995; Loeb et al., 1997). These hypotheses are supported by multi-year coherence among physical and biological parameters monitored throughout the southwest Atlantic sector (SC-CAMLR, 1998, Report of the Workshop on Area 48) and concordance in the interannual fluctuations of krill abundance at widely spaced sampling sites (Brierley et al., 1999).

The fishery on Antarctic krill may be of interest as a model for fishery management development for several reasons: (1) it is targeted on a prey species; (2) it is controlled by an international agreement; (3) this agreement is committed to preserving the stability and diversity of the pelagic ecosystem; and (4) the kinds of information required to manage the fishery and the decision rules for its use are evolving as we learn more about the system. Many fisheries throughout the world share one or more of these characteristics, and the lessons that can be derived from the Antarctic krill fishery may have wide applicability.

In this review, first we describe the political context and management approach of CCAMLR, including both strengths and weaknesses. Then we briefly review the current understanding of the natural history of Antarctic krill, its population response to environmental variability, its trophic position in the pelagic ecosystem, and the status of the fishery on krill. We describe the model used to estimate the yield of krill and its assumptions. We describe management implications with reference to two vectors of uncertainty: one regarding the nature of krill population variability and the other regarding the future development of the fishery. Then we discuss the likelihood of future scenarios and the management options available to CCAMLR. We suggest an evolving krill management scheme wherein: (1) key processes that appear to be instrumental in structuring the pelagic ecosystem and determining the productivity of the krill resource are identified and monitored; (2) decision rules based on indicators of key processes are elaborated; and (3) a research strategy is pursued with the objectives of monitoring performance and refining the scheme when appropriate. Finally, we conclude with a comment regarding the necessity of a precautionary philosophy in the context of imperfect and incomplete information.

Our emphasis is on the southwest Atlantic sector of the Southern Ocean, but we suggest that our comments may be applicable to the management of the Antarctic krill resource elsewhere in its range. The southwest Atlantic sector of the Southern Ocean (Scotia Sea), stretching from the Antarctic Peninsula to the South Sandwich Islands, has long been identified as the area of highest krill concentration (Marr, 1962). To date, 89% of the global harvest of Antarctic krill has been taken from this sector. CCAMLR has treated the krill in this area as a *de facto* management unit by establishing a precautionary harvest limit based on an estimated biomass of 35 million tons. The designation is somewhat arbitrary, however, and appears to be based on considerations that fishing effort has been concentrated in the vicinity of the South Shetland, South Orkney, and South Georgia archipelagos, that these islands are located along the Scotia Ridge which defines an oceanic basin referred to as the Scotia Sea, and that survey estimates were available from the Scotia Sea with which to scale a population model. Much, but certainly not all, of the scientific research on krill has focused on this region as well.

II. CONVENTION FOR THE CONSERVATION OF ANTARCTIC MARINE LIVING RESOURCES (CCAMLR)

A. POLITICAL CONTEXT

Intense and sporadic cycles of exploitation of marine living resources in the Southern Ocean began in the eighteenth century when fur seals were harvested close to extinction. The hunting of elephant seals, southern right whales, and some sub-Antarctic penguin species followed in the nineteenth century. More recently, in the early mid-twentieth century heightened whaling pressures forced the collapse of many of the great whale populations while exploratory harvests of ice seals were initiated (see McElroy, 1984; Kock, 1994; Agnew and Nicol, 1996 for reviews). Today, all of the formerly exploited marine mammal populations are protected, but controlled harvesting in the Southern ocean continues with fishing for fin-fish (many species of which are already severely depleted) and krill.

In the 1960s, the prevailing estimates of the annual production of Antarctic krill were large, ranging from 75 million to 700 million tons.* As the whale and fin-fish stocks grew scarce, distant water fishing nations became interested in krill as a resource. Because krill often dominates macro-zooplankton assemblages (comprising 75 to 90% of the biomass in some areas of the Southern Ocean), it is not surprising that they have been viewed as the ocean's largest harvestable population (Schnack-Schiel and Mujica, 1994; Marschall, 1988). The fishery expanded quickly in the late 1970s and fleets from several nations began fishing for krill (Table 1). As the new international fishery grew, so did concerns about

* More recent estimates have narrowed the range from 64 to 137 million tons (Nicol et al., in press).

TABLE 1

Total Catch of Krill (Metric Tons) in Convention Area by Country and Split Year (July 1 through June 30). Catches from 1998/99 Are from Preliminary Reports to CCAMLR

Year	Japan	Panama	Latvia	Chile	Poland	Korea	USSR	Russia	Ukraine	Great Britain	Germany	Spain	Argentina	Total
1998/99	71,022	0	0	0	16,285	1,231	-	0	5,694	0	0	0	4,427	98,659
1997/98	63,233	0	0	0	15,312	1,623	-	0		634	0	0	0	80,802
1996/97	58,798	0	0	0	19,156	0	-	0	4,246	308	0	0	0	82,508
1995/96	60,546	496	0	0	20,610	0	-	0	20,056	0	0	0	0	101,708
1994/95	60,303	141	0	0	9,384	0	-	0	48,886	0	0	0	0	118,714
1993/94	62,322	0	71	3,834	7,915	0	-	965	8,852	0	3	0	0	83,962
1992/93	59,272	0	0	3,261	15,909	0	-	4,249	6,083	0	0	0	0	88,774
1991/92	74,325	0	0	6,066	8,607	519	-	151,725	61,719	0	0	0	0	302,961
1990/91	67,582	0	0	3,679	9,571	1,210	275,495	-	-	0	0	0	0	357,537
1989/90	62,187	0	0	4,501	1,275	4,039	302,376	-	-	0	396	0	0	374,774
1988/89	78,928	0	0	5,329	7,798	1,779	301,498	-	-	0	0	0	0	395,332
1987/88	73,112	0	0	5,938	5,215	1,525	284,873	-	-	0	0	0	0	370,663
1986/87	78,360	0	0	4,063	1,726	1,527	290,401	-	-	0	0	379	0	376,456
1985/86	61,074	0	0	3,264	2,065	0	379,270	-	-	0	0	0	0	445,673
1984/85	38,274	0	0	2,598	0	0	150,538	-	-	0	50	0	0	191,460
1983/84	49,531	0	0	1,649	0	5,314	74,381	-	-	0	0	0	0	130,875
1982/83	42,282	0	0	3,752	360	1,959	180,290	-	-	0	0	0	0	228,643
1981/82	35,116	0	0	0	0	1,429	491,656	-	-	0	0	0	0	528,201
1980/81	27,698	0	0	0	0	0	420,434	-	-	0	0	0	0	448,132

the potential overexploitation of this species, which is central to the natural economy of the Southern Ocean (Laws, 1985). Following the collapse of whale and seal fisheries, nations were eager to maintain the krill fishery at sustainable levels, thereby protecting both the developing fishery and the Antarctic marine ecosystem (Miller, 1991; Nicol, 1991a,b; Croxall et al., 1992).

As interest in the krill resource grew, the international scientific community began to focus attention on the status of krill populations. In the early 1980s, SCAR (the Scientific Committee on Antarctic Research) organized the BIOMASS Program (Biological Investigation of Antarctic Systems and Stocks) and directed attention to the abundance, distribution, and dynamics of krill in the Southern Ocean. BIOMASS, the largest and most ambitious ecosystem program ever launched in the Southern Ocean (Stokke, 1996), consisted of three major phases: FIBEX (First International Biomass Experiment) in 1981, SIBEX (Second International Biomass Experiment) in 1983/84, and SIBEX II in 1984/85. These were multinational, multiship initiatives, that conducted large-scale acoustic surveys for krill over large areas of the Southern Ocean. Acoustic data collected during FIBEX were later used to estimate the biomass of krill in the southwestern Atlantic sector of the Southern Ocean (Trathan et al., 1992), and this estimate is the current basis for CCAMLR's determination of a precautionary krill yield for this region.

Concurrent with the emergence of BIOMASS, the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) took form in the late-1970s during negotiations between the Antarctic Treaty Consultative Parties. The Consultative Parties had three major concerns in mind when drawing up CCAMLR: (1) the conservation of krill stocks in the event of a rapidly expanding fishery; (2) avoidance of conflict over sovereignty claims between claimant and nonclaimant states vying for control of certain Antarctic territories; and (3) the Consultative Parties' retention of authority over Antarctic affairs in the face of increasing interest by the United Nation's Food and Agricultural Organization (FAO) (Lagoni, 1984; Vicuna 1996; Stokke, 1996).

CCAMLR negotiating parties solved the sovereignty issue — the question of maritime jurisdiction relating to islands within CCAMLR boundaries under recognized sovereignty of contracting parties — by means of carefully drafted ambiguous language in the Convention that allows both claimants and non-claimants to find support for their respective policies. Countries claiming territories within CCAMLR's proposed jurisdictional boundaries were concerned that their claims to exclusive economic zones (EEZs) remain legitimate irrespective of the new fisheries arrangement. At present, the EEZ claims relating to the Antarctic continent are not being enforced and therefore do not normally affect fisheries management. Furthermore, all contracting parties to CCAMLR have agreed to form a joint jurisdiction over fisheries, which is channeled through national institutions under the terms of the Convention. In this context, EEZ claims have not been rejected but harmonized under an agreed mechanism for international fisheries management. The acceptance of CCAMLR by FAO, which expressed considerable interest in developing a competing regime for Antarctic resource management, was solved by the incorporation of a unique "ecosystem approach" to management. This concept, introduced by CCAMLR for the first time in an international fisheries convention, was considered a great achievement by FAO and prompted its acknowledgement of CCAMLR's regulatory authority. As a result, nations drafting CCAMLR were effective in both diverting potential EEZ claims by states asserting Antarctic territorial rights and in retaining resource management authority by placating FAO. The ultimate result of these negotiations was a unique treaty for the management of Antarctic marine living resources, complete with an ecosystem approach and a consensus-based decision procedure that gave distant water fishing nations the veto, and hence continued control over their actions.

There are 23 full members of CCAMLR, including the original Antarctic Treaty signatories and most of the nations currently fishing in the Antarctic ecosystem, as well as several acceding nations who are present at CCAMLR meetings as observers.* The CCAMLR regime consists of two primary bodies: a Commission and a Scientific Committee. The Commission functions as the central administrator and policymaking organ for CCAMLR, while the Scientific Committee is intended to be a consultative body for the exchange of scientific information and the formulation of recommendations to the Commission. By design, members of the Scientific Committee discuss a range of ideas and recommendations, reach agreement on issues through a modified peer review process rather than by consensus, and forward to the Commission those conclusions deemed most meritorious while remaining politically unbiased. In practice, Working Groups, reporting to the Scientific Committee, perform much of this work and political bias is difficult to completely eliminate. Nevertheless, the structure allows the Commission to make informed decisions based on the best available science. CCAMLR decisions are adopted by consensus in the Commission and become legally binding on members after 180 days should no objections be lodged.

* Current members of CCAMLR as of 1999 are Argentina, Australia, Belgium, Brazil, Chile, EEC, France, Germany, India, Italy, Japan, Korea, New Zealand, Norway, Poland, Russian federation, South Africa, Spain, Sweden, Ukraine, United Kingdom, the United States, and Uruguay.

B. THE CONVENTION

The Convention applies to all marine living resources inside an area whose northern boundary is roughly delineated by the mean position of the Antarctic Polar Front and thus follows the major physical and biological boundaries of the Southern Ocean.** The Convention area is divided into three sectors (Atlantic, Indian, and Pacific Ocean sectors) which for reporting purposes are termed FAO Statistical Areas 48, 58, and 88, respectively. Each area is divided into a number of subareas and divisions (Figure 1). With reference to the southwest Atlantic sector, Subarea 48.1 contains the fishing areas around the South Shetland Islands, Subarea 48.2 contains the fishing areas around the South Orkney Islands, and Subarea 48.3 contains the fishing areas around South Georgia.

The Convention is an ambitious document. Most fisheries agreements call for the management of single species in isolation, which is not surprising given that such reactive agreements usually follow substantial stock depletion. For the first time in history, a pro-active fisheries regime was established with a mandate to regulate with a holistic as opposed to a single species approach (Nicol, 1991a,b; Miller, 1991; Agnew and Nicol, 1996). This ecosystem approach to management is evident in Article II of the Convention, which states:

1. The objective of this Convention is the conservation of Antarctic marine living resources.
2. For the purposes of this Convention, the term "conservation" includes rational use.
3. Any harvesting and associated activities shall be conducted in accordance with the following principles of conservation:

(a) Prevention of decrease in the size of any harvested population to levels below those that would ensure its stable recruitment;

(b) Maintenance of the ecological relationships between harvested, dependent, and related populations of Antarctic marine living resources and the restoration of depleted populations to levels ensuring stable recruitment;

(c) Prevention of changes or minimization of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades, taking into account the state of available

** Exceptions to CCAMLR's authority are the International Whaling Commission and the Convention for the Conservation of Antarctic Seals, which have priority over matters of cetaceans and pinnipeds, respectively.

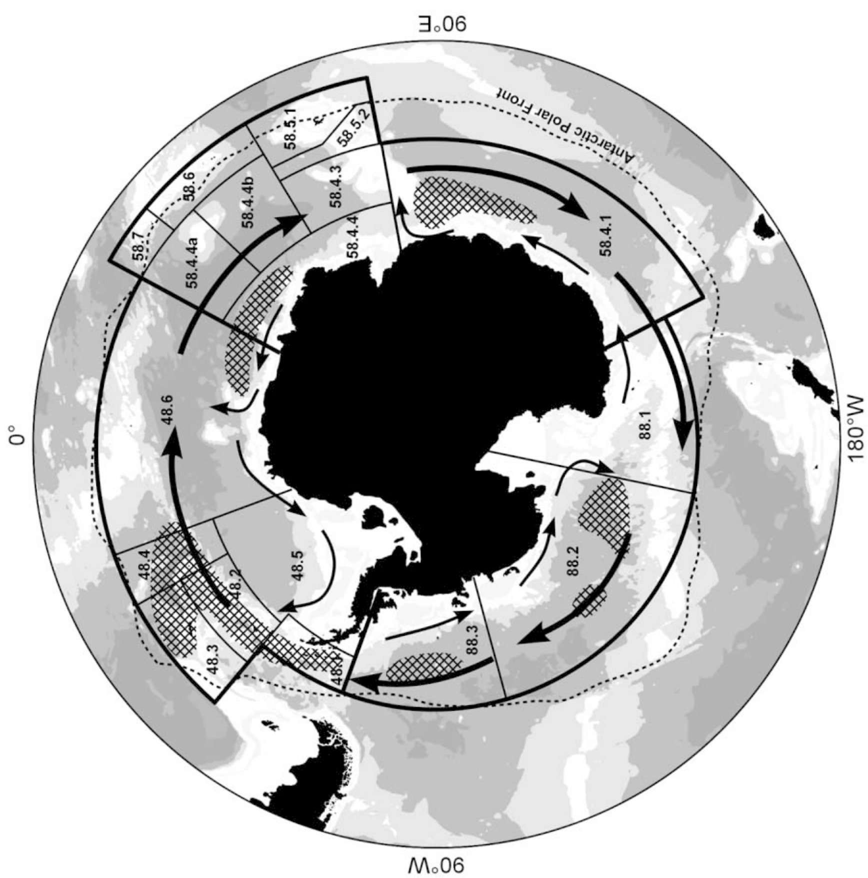

FIGURE 1. Antarctic Polar Front, CCAMLR boundaries, FAO Statistical areas, areas of high Krill densities (cross-hatched), Antarctic Circumpolar Current (West Wind drift) and East Wind Drift (sources: Convention for the Conservation of Antarctic Marine Living resources, Hobart, Australia; Laws, 1985; Amos, 1984; MacIntosh, 1973.)

> knowledge of the direct and indirect impacts of harvesting, the effect of introduction of alien species, the effects of associated activities on the marine ecosystem and the effects of environmental changes, with the aim of making possible the sustained conservation of Antarctic marine living resources.

This article extends the principles of management of commercial harvest to a complex suite of inter-linked units and systems, calling for both the maintenance of ecological relationships between harvested, dependent, and related populations and prevention of changes, or minimization of the risk of changes, in the marine ecosystem. Furthermore, Article II mandates that CCAMLR account for the effects of environmental changes as well as harvesting on the ecosystem, emphasizing the need for CCAMLR to incorporate the nature of environmental variability into management decisions.

The Convention's Article II combines this "ecosystem approach" to management with a complementary "precautionary approach," stipulating that decisions should not be taken that have a high risk of long-term adverse effects. The Convention does not specify exactly how this level of risk should be determined, an inherent ambiguity that complicates CCAMLR management efforts. The document only states that "ecosystem changes" must be reversible over two or three decades and that decisions must take into account all available information of the direct and indirect impacts of human activities. This precautionary approach has important implications when dealing with high levels of scientific uncertainty, as, for instance, when the actual biomass or recruitment of exploited stocks are not known.

While the novel proactive regulatory approach embedded in CCAMLR is a step toward successful resource management, it is wrought with difficulties. Major obstacles include: (1) the novelty of the ecosystem approach; (2) the absence of information and the question of action in a state of ignorance; and (3) the requirement for consensus (Hoffman, 1984). Ecological uncertainty combined with a unanimous vote required to pass conservation measures (not including abstaining members) was interpreted as a potential impediment to achieving consensual action on catch limits (Butterworth, 1986; Stokke, 1996). Initially, the Commission split into two camps: (1) the fishing nations that sought to ensure their rights of rational harvest, and (2) the nonfishing nations that believed conservation and caution should be stressed. Conflicts between development and conservation existed for much of CCAMLR's history and the scientific information guiding this debate was slow to emerge (Nicol and de la Mare, 1993).

C. IMPLEMENTATION OF THE CONVENTION

Initial efforts at resource management by CCAMLR showed poor results. Confrontational attitudes prevailed and conservation measures were either nonexistent or scarce, in many cases falling well below required levels of protection. Initial efforts were stock specific rather than holistic and directed at the already depleted finfish fisheries in dire need of regulation (Vicuna, 1996). The krill fishery, being relatively small when compared with estimates of annual krill consumption, was a lesser concern. The necessary scientific information regarding the status of krill stocks and other ecosystem components was practically nonexistent, and few countries submitted more than basic statistical data. A number of fishing nations exhibited unwillingness to move faster than the absolute minimum, stating scientific uncertainties as a reason for not acting. Stokke (1996) maintained that these nations, eager to protect their fledgling industries, acted on the presumption that no management measures should be taken unless they were certain to have a positive impact on the krill fishery. Furthermore, the Commission and its Secretariat were slow in determining what data were really needed and in establishing mechanisms for ensuring that data were submitted properly. As a result, it took the Commission 10 years to finally set a precautionary catch limit for krill. In the meantime, the krill harvest approached a half a million tons in the 1980 to 1981 season. Although seemingly large, this quantity remained far below the estimates of annual krill production, and the threat of imminent overexploitation of krill was minimal (Kock, 1994; Agnew and Nicol, 1996; Nicol and Endo, 1999).

Since 1987, CCAMLR's effectiveness has improved rapidly. The political nature of decision making became more integrated with scientific and technical knowledge, cooperation between the CCAMLR member nations became the normal practice, and consensual agreements were more easily reached. As a result, conservation measures became stronger and more comprehensive (Davis, 1996). An ecosystem-monitoring program (outlined below) was established in 1987, and the first precautionary limits on krill harvest were established in 1991, when annual catch in the southwest Atlantic sector was restricted to 1.5 million metric tons. The change in CCAMLR performance is partly due to economic considerations. The discovery of high fluoride levels in krill exoskeletons and problems in processing and marketing slowed the development of the fishery after 1982 and reduced the economic incentive of fishing nations to oppose the conservation-minded majority in CCAMLR (Vicuna, 1996; Nicol and Endo, 1999). Political and economic disruptions in the fishing states (Russia and the Ukraine) of the former Soviet Union, which until

1992 were major harvesters of krill, reduced their influence and must also be considered a contributing factor. The reactive policy of the 1980s gradually gave way to a precautionary approach for krill in the 1990s. This new approach is visible in CCAMLR's management record: 80% of CCAMLR conservation measures have been adopted by the Commission since 1990.

At present, CCAMLR attempts to implement the major portion of its mandates through work conducted voluntarily by member countries. These include directed scientific research, modeling studies, and participation in the CCAMLR Ecosystem Monitoring Program (CEMP). In addition, the CCAMLR Secretariat collects, organizes, and archives data from four principal sources: (1) fishery catch and effort statistics provided by members engaging in commercial fishing, (2) biological information on by-catch of fish and incidental mortality of seabirds and marine mammals when collected by observers during fishing operations (at present, observers in the krill fishery are not mandatory), (3) biological information and biomass estimates obtained during fishery-independent scientific surveys as submitted by member countries, and (4) biological information on dependent species collected by member countries, as part of CEMP (Agnew, 1997). The overall effectiveness of CCAMLR, however, remains dependent on the willingness of member nations to take on tasks that have been deemed important by the Scientific Committee and the Commission.

CCAMLR established CEMP under the premise that monitoring and regulating all facets of a marine ecosystem was an ambitious endeavor for which neither sufficient knowledge nor adequate tools exist. The Scientific Committee selected a range of higher trophic level species, or indicator species, likely to reflect changes in the availability of krill. The selection of indicator species was based on the criteria that they should feed predominantly on krill, have a wide geographic distribution, and represent important ecosystem components. The present list of monitored dependent species includes: crabeater and Antarctic fur seals, Adelie, chinstrap, gentoo and macaroni penguins, Antarctic and cape petrels, and black-browed albatrosses. The intention was to establish a number of land-based predator monitoring sites in a variety of locations throughout the southwest Atlantic sector and other sites in the Southern Ocean. These sites would be placed such that distinctions between broad scale and local scale changes as well as fishery-induced vs. natural changes could be detected. Several parameters were identified to be monitored for each species, and organized into four groups: (1) reproduction; (2) growth and condition; (3) feeding ecology and behavior; and (4) abundance and distribution (SC-CAMLR, 1985). In order to facilitate statistical comparisons between monitoring sites, the Scientific Committee agreed to a set of standard methods. The data are contributed to and managed by a centralized, standardized system operated by CCAMLR. At present, field work is conducted voluntarily by 9 out of the 23 CCAMLR member states. Environmental parameters such as meteorological conditions, hydrographic indices, and sea ice extent are also monitored.

Krill density and biological parameters (e.g., mortality, recruitment) are estimated from fisheries data and scientific surveys. Acoustic and net sampling data collected as part of the FIBEX and SIBEX krill surveys during the international BIOMASS Program in the early 1980s was used to estimate krill biomass over large portions of the southwest Atlantic (Trathan et al., 1992) and forms the basis for the precautionary limit on krill harvest established by CCAMLR for Subareas 48.1, 48.2, and 48.3. A similar broad-area survey was conducted by Australia in 1994 (Pauly et al., 1996) in order to provide a basis for establishing a precautionary limit for Subarea 58.4.1. Long-term survey efforts on a more localized basis have been conducted by several countries near the South Shetland Islands and South Georgia (e.g., Hewitt and Demer, 1993 and 1994; Brierley et al., 1997).

III. THE KRILL RESOURCE IN THE SOUTHWEST ATLANTIC SECTOR OF THE SOUTHERN OCEAN

A. LIFE HISTORY

Of the 85 species of euphausiids worldwide, Mauchline and Fisher (1969) list 9 that are most important in terms of their numbers and function in marine ecosystems. Of these nine species, Antarctic krill (Figure 2) is the largest, the longest lived, and constitute the greatest biomass. While the species can be found throughout the Southern Ocean, the highest densities appear to be associated with permanent large-scale cyclonic eddies (Amos, 1984, Figure 1). These gyres are associated with topographic features that influence the eastward flowing Antarctic Circumpolar Current (ACC, also known as the West Wind Drift), and create exchanges with the East Wind Drift, the latter flowing westward near the continent (Deacon, 1984). Mackintosh (1973) identified areas of high krill density associated with the northern extension of the Weddell Gyre (Scotia Arc Weddell stock), and the East Wind Drift between 20° and 50° East Longitude (Enderby Stock) and between 85° and 100° East Longitude (Kerguelen-Gausberg stock). Additional regions

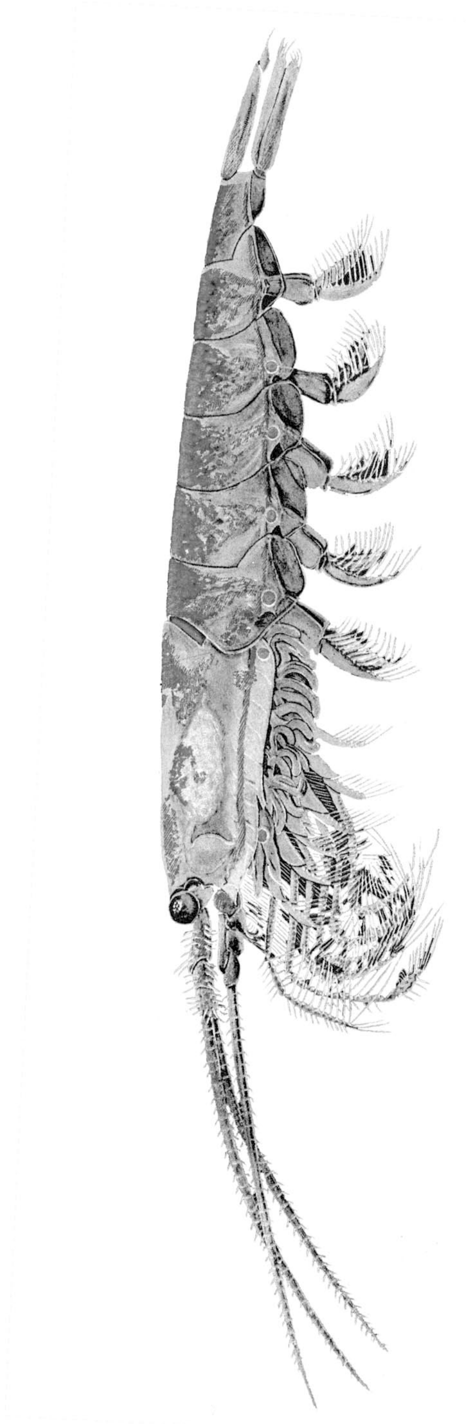

FIGURE 2. Antarctic krill (*Euphausia superba* Dana) (Redrawn from Bargmann, 1937 by D. A. Demer.)

of high krill densities are associated with the northern extensions of gyres in Ross and Bellingshausen Seas. Several authors (Marr, 1962; Amos, 1984; Priddle et al., 1988; Miller and Hampton, 1989) have noted the latitudinal asymmetry between krill associated with the eastward-flowing northern limbs of gyres (e.g., southwest Atlantic sector) and those associated with the westward-flowing southern limbs of gyres (e.g., Indian and Pacific sectors). The largest concentration of krill is present in the southwest Atlantic sector (Marr, 1962), along with large numbers of krill-consuming birds, seals, and whales, and it is here that the greatest geographic overlap between krill and their vertebrate predators also occurs (Laws, 1985).

Early genetic studies, based on allozyme frequencies, failed to distinguish subpopulation structure, and Antarctic krill were considered to behave as a single breeding unit (Fevolden and Schneppenheim, 1989). A more recent study (Zane et al., 1998), based on mitochondrial DNA sequences, demonstrated population genetic differences between samples obtained from the eastern Weddell Sea and from the waters around South Georgia. The differences between these samples were larger than those between samples from South Georgia, the Ross Sea, and the Bellingshausen Sea, suggesting genetic isolation of krill in the Weddell Sea gyre (Zane et al., 1998). This is consistent with the distinction drawn between Bellingshausen Sea krill and Weddell Sea krill by Siegel (1982) and Siegel et al. (1990) based on morphometric considerations. Zane et al. 1998 also note, however, that their results could be explained by genetic drift in response to the observed high variability in krill reproductive success (Loeb et al., 1997).

In the southwest Atlantic sector of the Southern Ocean, Antarctic krill spawn in the summer in the vicinity of the South Shetland and South Orkney Islands; although krill are abundant further to the north and east near South Georgia, they do not apparently spawn there (Fraser, 1936; Figure 3). During the spring and early summer, spawning occurs in the upper water column in offshore areas. Initially, the eggs sink and hatch at depths of 1000 m or more. The larvae ascend to the surface passing through as many as 10 stages (Marr, 1962; Hempel and Hempel, 1986). Krill larvae continue to grow through the summer and fall and eventually metamorphose into juveniles sometime during the winter or early spring of the following year. Antarctic krill are considered to live for at least 5 or 6 years according to field data (Siegel, 1987) and perhaps as long as 10 years according to experimental data (Ikeda, 1987; Nicol, 1990).

Krill density and dispersion patterns appear to be correlated with both reproductive activity and water movements. During the summer breeding season, a spatial succession of age groups occurs with the

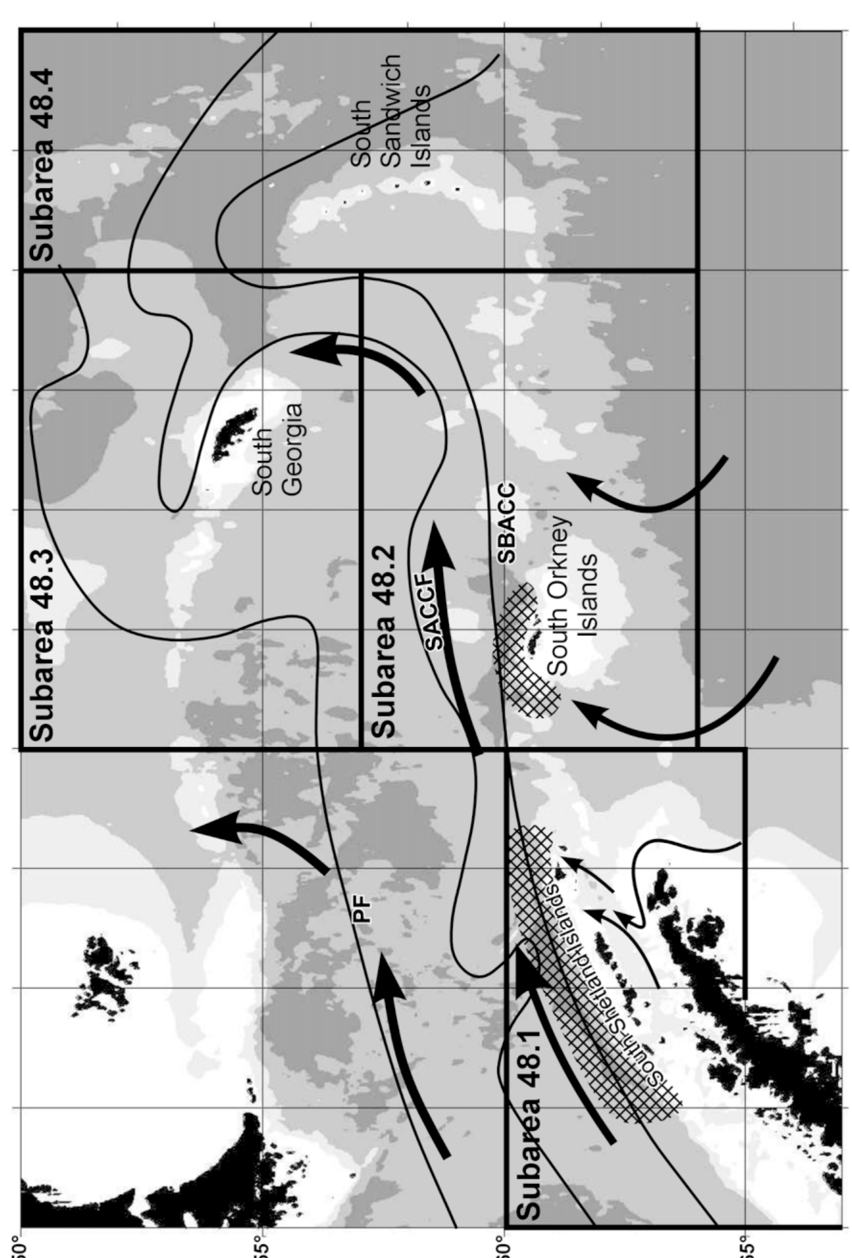

FIGURE 3. Krill spawning areas (cross-hatched), major currents and frontal zones in the southwest Atlantic sector of the Southern Ocean; PF indicates Polar Front, SACCF indicates Southern Antarctic Circumpolar Current Front and SBACC indicates the southern boundary of the Antarctic Circumpolar Current (sources: Marr, 1962; Orsi et al., 1995; Hofmann et al., 1998.)

juveniles located inshore and the breeding adults moving offshore (Siegel, 1988; Siegel et al., 1997). This spatial segregation is complicated by the actions of hydrographic patterns, which also have a large effect on krill distribution. The highest densities of krill biomass occur in regions with the most complex water mass structure, above the continental shelf slope of the Antarctic Peninsula (Stein and Rakusa-Suszczewski, 1984; Makarov et al., 1988; Pakhomov and McQuaid, 1996). This illustrates that bottom topography affects the direction of water movements and that zones of convergence, eddies, and gyres are the primary loci for krill concentrations (Witek, 1988).

In the southwest Atlantic sector krill appear to move eastward with the Antarctic Circumpolar Current (ACC), although the relative importance of passive transport vs. active migration (either to maintain or change position) is uncertain. A seasonal pattern of variation in krill abundance along the northwestern side of the Antarctic Peninsula is apparent. Krill abundance is low during the winter, starts to increase during November (austral spring), and reaches a maximum by the end of December (Siegel, 1988). The maximum can be observed until late February. There is some interannual variation in this seasonal trend, and the period can shift by approximately 4 weeks to an earlier start or a later end of the cycle. From March onward, krill abundance declines rapidly; the difference between the summer peak and the winter minimum can be several orders of magnitude (Siegel, 1988; Siegel et al., 1997). Spiridonov (1995) reported that the beginning of spawning in the vicinity of the South Shetland and South Orkney Islands was highly variable within a 2 to 3 month time frame, starting as early as December or as late as February and extending for as long as 3 months.

Large interannual variations in krill recruitment and density have been observed near the South Shetland Islands over the last 20 years (Siegel and Loeb, 1995; Loeb et al., 1997; Siegel et al., 1998). During any particular year the age structure of the population appears to be dominated by one or two age classes. It is also apparent that these strong year classes are autocorrelated in time, that is, several poor years of reproductive success are followed by 1 to 2 good years, describing a repeating cycle with a 4 to 5 year period. Krill abundance, viewed as the sum of all age classes in the population, is cyclic as well, declining with successive decreases in reproductive success and increasing dramatically with the recruitment of strong year classes. Three relatively strong year classes, produced from spawning in 1986/87, 1990/91, and 1994/95, have apparently sustained the population during the last decade (Loeb et al., 1997; Siegel et al., 1998). Krill appear to be seasonal visitors to the South Shetland area, but the data presented by Siegel, Loeb, and their colleagues suggest that the relative contribution of year classes, and their affect on population size can be tracked over several years by sampling in the area during the spring and summer months.

B. INFLUENCE OF SEA ICE, SALPS, AND ADVECTION

During winter months, pack ice dominates the Antarctic marine ecosystem, effectively doubling the surface area of the Antarctic continent from summer to winter. Both larval and adult krill congregate and feed on algae under the seasonal ice cover, and it has been suggested that the ice may provide both shelter and food to overwintering krill (Marschall, 1988, Bergström et al., 1990; Siegel et al., 1990; Melnikov and Spiridonov, 1996; Nicol and Allison, 1997). In addition, marginal ice zones (the interface between the seasonal sea ice and the open ocean) are loci for phytoplankton blooms because the ice retreats in the spring (Smith et al., 1988; Priddle et al., 1992). Daly and Macaulay (1991) suggested that adult krill rely on the sea ice habitat to maintain energy supplies and promote development of reproductive systems during the Antarctic winter and early spring. These views were corroborated by log book catch data from Japanese krill trawlers, which showed a positive correlation between the degree of sea ice cover in the austral winter and the abundance of small krill the following summer (Kawaguchi and Satake, 1994).

The annual extent of winter sea ice development in the Antarctic Peninsula region describes temporal cycles similar to that observed in krill reproductive success (Loeb et al., 1997). Over the last 20 years there have been four "ice events" when the sea ice covered larger than average areas of the ocean over longer than average periods of time (Hewitt, 1997). Each of these events was associated with strong krill year classes (Figure 4).

The abundance of the salp (*Salpa thompsoni*) in the Antarctic Peninsula region also undergoes cyclic variations, but these are 180 degrees out of phase with that of krill reproductive success (Loeb et al., 1997). Salps are planktonic filter feeders that pump water through gelatinous cylindrical-shaped bodies and trap particles on mucous membranes. They are omnivorous encounter feeders consuming phytoplankton, fish eggs, and other micro-zooplankton. Throughout the spring and summer salps reproduce asexually, budding off clones in long chains comprised of several hundred individuals. When fully grown these chains may attain lengths of a meter or more. A single animal can make several chains thus vastly contributing to population growth. The long chains, although fragile, move and act like a single organism. Toward the end of the summer individual clones mate sexually and a solitary embryo is

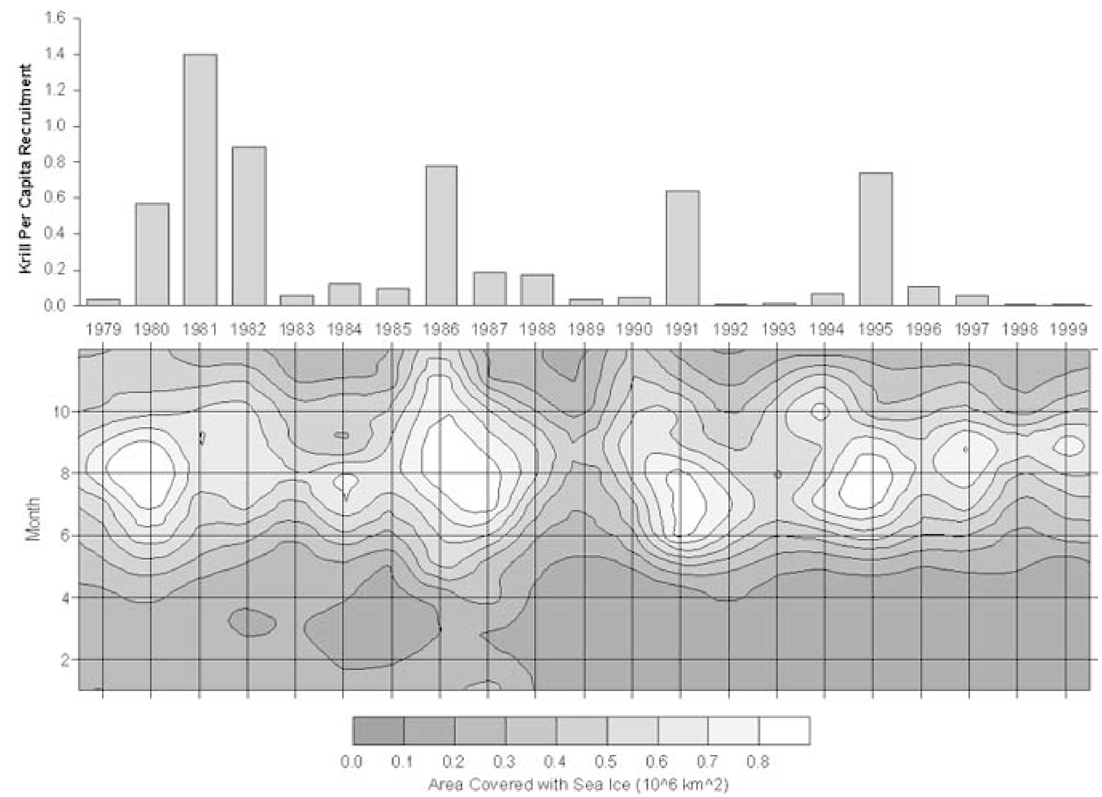

FIGURE 4. Seasonal and interannual variability in sea ice extent and percapita krill recruitment as observed in the Antarctic Peninsula area. (Sources: Hewitt, 1997, in press, V. Loeb and V. Siegel, personal communication.)

formed and incubated within each animal. The embryo eventually emerges, overwinters, and begins to clone itself the following spring, repeating the pattern of alternating sexual and asexual generations. The salp population experiences multiyear cycles in abundance, varying 100-fold from years with the lowest abundances to those with the highest. Years of high salp abundance are associated with years of poor krill reproductive success and winters of low sea ice extent (Loeb et al., 1997).

Siegel and Loeb (1995) proposed that extensive sea ice development is beneficial to over-wintering krill by providing a refuge and access to food in the form of algae on the underside of the ice. During the spring retreat of sea ice well-fed adult krill emerge, feed on phytoplankton in the water column, elaborate reproductive material, and start to spawn. With optimal feeding conditions they produce several batches of eggs over several months. The eggs sink and hatch into larvae, which eventually return to the surface layers and feed on phytoplankton. Larvae hatching early in the summer enjoy a longer growing period and are presumed to be better fit to survive through the winter than those hatched later in the season. A second winter of extensive ice cover further enhances the survival of these larvae, which metamorphose into juvenile krill sometime during the winter and early spring.

Loeb et al. (1997) proposed that salps may play an even more important regulatory role on krill reproductive success, depending on the size of their overwintering generation. If a sufficient "seed population" is present during years with poor sea ice cover (or early sea ice retreat) solitary salps may begin to bud during the late winter, rapidly expanding the population and consuming a substantial portion of the spring phytoplankton bloom. Poorly nourished adult krill may not be able to spawn early in the season and during years with very high salp abundances may not spawn at all. Salps may pose another threat by filter feeding on whatever krill eggs are produced (Nishikawa et al., 1995).

While direct evidence for many of these mechanisms is currently lacking, observations of krill demographics and abundance, salp densities, and sea ice extent over the last 2 decades near the South Shetland Islands demonstrate that: (1) krill recruitment is positively correlated with early seasonal spawning (in December-February) and both are correlated with extent of sea ice extent during the winters before and after spawning, and (2) poor krill recruitment and late spawning are associated with reduced sea ice extent and high salp abundance (Siegel and Loeb, 1995; Loeb, et al., 1997).

Superimposed on these cycles in the Antarctic Peninsula region is a well-documented long-term warming trend since the mid-1940s (Vaughan and Doake, 1996). The most complete documentation is air temperatures measured at land bases which show a strong negative correlation with indices of sea ice extent during the last 2 decades (Smith et al., 1996 and 1998). In concert with the long-term warming trend, the frequency of winters with extensive sea ice development appears to have decreased (Hewitt, 1997) and the frequency of springs with extensive salp blooms appears to have increased (Loeb et al., 1997). The phenomenon of rapid salp population growth is of additional concern because salps, even when abundant do not appear to be a dominant part of the diet of vertebrate predators on krill and, as such, may modify the pelagic food web by sequestering a substantial portion of primary production and expelling it to deeper waters as fecal pellets and/or dead bodies (Fortier et al., 1994; Madin and Kremer, 1995). If the Siegel-Loeb hypothesis is correct, a reduction in the frequency of extensive ice winters will lead to a reduction in the frequency of strong krill year classes and a lower krill median population size, an increase in the median salp population size, and a change in the structure of the pelagic food web. Ultimately, this may mean a reduction in the levels of krill-dependent predator populations.

High interannual variability in krill abundance has also been observed at South Georgia (Brierley et al., 1997). Krill do not appear to spawn near South Georgia and must be transported there from sources upstream. Strong and weak krill year classes observed near the South Shetland Islands are apparent in observations made near South Georgia (Brierley et al., 1999). These observations support the hypothesis that krill are transported into the area from the Bellingshausen Sea through the South Shetland and South Orkney regions via the ACC (Siegel, 1986; Hofmann et al., 1998). Occasionally, however, there are regional differences between the regions in the size composition of sampled krill, and it has been suggested that this could be caused by transport of Weddell Sea krill into the region of South Georgia (Everson, 1977). Variations in the position of the ACC could act to change the mixture Bellinshausena and Weddell Sea of krill in the vicinity of South Georgia (Priddle et al., 1988; Hofmann et al., 1998).

Huntley and Niiler (1995) stressed the importance of advective transport on the observed variations in density and demographic structure of krill. They argued that the spatial variability and intensity of advection in the Antarctic Peninsula region could act to separate larval krill from the adults and destroy the demographic integrity of the population. In such a manner, successful reproduction in the Antarctic Peninsula area could be apparent as high numbers of juvenile krill off South Georgia but absent from samples in the Peninsula area. On a broader scale, Tynan (1998) noted that krill distribution is linked to the southern boundary of the ACC and proposed that the reproductive strategy of krill has evolved in response to the thermal structure of deeper water masses at the boundary. Variability in the position and structure of the boundary thus could have important affects on the distribution, development, and feeding success of krill. Moreover, variations in sea ice and advection may not be independent. Several authors (e.g., Murphy et al., 1988; White and Petersen, 1996; Stammerjohn and Smith, 1996) have demonstrated links between properties of the atmosphere, ocean, and sea ice. For example, the latitudinal position of the Weddell-Scotia Sea boundary is thought to be determined by the intensity of the Weddell gyre, which in turn is driven by the formation of dense and cold Weddell Sea water (Fedulov and Shnar, 1990). Foster and Middleton (1980) note that the principal factor in the creation of cold Weddell Sea water is increased salinity resulting from sea ice formation. Thus, warm or cold years, which may augment or hamper sea ice formation, may also influence the intensity of the Weddell Sea gyre and consequently the position of its boundary with the ACC.

C. PREDATION ON KRILL

The importance of krill to the structure of the Antarctic marine ecosystem is impressive. Numerous populations of krill predators, including fur seals, penguins, and other seabirds, populate the South Shetland, the South Orkney, and South Georgia archipelagos. These land-breeding predators rely on ample concentrations of krill within their foraging ranges to sustain them and their offspring during the critical summer breeding season. Croll and Tershy (1998) estimate that 830,000 tons of krill are required during the summer season in order to maintain current population levels of penguins and seals breeding on the South Shetland Islands. Everson and de la Mare (1996), summarizing calculations made by Croxall et al. (1984, 1985) estimate that 9,760,000 tons of krill are consumed by land-breeding krill predators near South Georgia during the summer months. Pelagic krill predators may consume more, but estimates of regional krill consumption are scarce. Everson (1984) estimated the annual consumption of krill throughout the Southern Ocean by baleen whales at 43 million tons, by seals at 128 million tons, by birds at 33 million tons, possibly 100 million tons by squid, and an unknown but substantial quantity by fish. Taken together these numbers indicate that a reasonable estimate of annual consumption of Antarctic krill by natural predators is between 150 and 300 million metric tons (Miller and Hampton, 1989; Everson and de la Mare, 1996). Assuming, albeit unrealistically, that predation pressure is evenly distributed throughout the

Southern Ocean, the annual consumption of krill in the southwest Atlantic sector (1985, 1985), would be between 16 and 32 million tons of krill (Everson and de la Mare, 1996).

The reproductive success of fur seals, as well as chinstrap, Adelie, and gentoo penguins monitored at selected breeding sites in the South Shetland Islands covaries with the local abundance of krill, but the dynamic range is much less (SC-CAMLR 1998, Report of the Workshop on Area 48). A reduction in the numbers of Adelie penguins breeding at in Admiralty Bay, King George Island, has been attributed to a reduction in the overwintering survival rate of post-fledglings rather than a reduction in breeding success (W. Trivelpiece, personal communication).

Observations of krill population structure, seasonal sea ice development, and krill predator reproductive performance at South Georgia describe cyclic fluctuations in phase with those observed in the South Shetland Islands (SC-CAMLR, 1998, Report of the Workshop on Area 48). Strong and weak year krill classes are evident in the diet of their predators at South Georgia and match those observed at the Antarctic Peninsula. The reproductive performance of krill predators at South Georgia undergoes larger variations than those observed at the South Shetland Islands or the South Orkney Islands. The occasional years of almost total reproductive failure at South Georgia correspond with years of low krill abundance in the Antarctic Peninsula region, which in turn follow several years of poor krill recruitment (Croxall et al., 1997, 1998; SC-CAMLR, 1998, Report of the Workshop on Area 48).

Observations at South Georgia appear to confirm the hypothesis that the reproductive success of krill predators is dependent on advective transport of krill from the Antarctic Peninsula area. This in turn suggests that observations of critical processes in the Antarctic Peninsula area may be important predictors of events across the Scotia Sea and, in particular, at South Georgia. It has also been suggested that some krill at South Georgia originate in the Weddell Sea and that meanders and changes in the position of frontal zones associated with the ACC axis act to adjust the mixture of krill from the two sources (SC-CAMLR 1998, Report of the Workshop on Area 48; Reid et al., 199a,b).

As a final comment on krill predation, it is important to note that current krill predator population levels may not reflect historical values. One hypothesis popular among early proponents of an intense fishery on krill asserted that the decimation of the blue and sei whales from commercial whaling resulted in krill biomass much higher than historic levels (see reviews of this idea in Laws, 1977; Croxall and Prince, 1979). Competitive release has been suggested as the cause for growth in the populations of Antarctic fur, crabeater, and leopard seals during the latter half of this century. Fur seal populations have been increasing at an annual rate of 10% (Payne, 1979, Boyd et al. 1990, 1995; Boyd, 1993); leopard and crabeater seals appear to be increasing at an annual rate of 7.5% (Laws, 1984), although the evidence is far less convincing. It is difficult, however, to separate the effects of increased krill availability from the recovery of overexploitation, particularly in the case of the fur seals. Furthermore, evidence of similar increases in seabird populations is somewhat inconclusive. Prevost (1981), for example, doubts that seabird populations have increased in response to the reduction of whale numbers. Conroy and White (1973) and Conroy (1975), Croxall et al. (1981) and Trathan et al. (1996), present information that suggests that populations of king, macaroni, Adelie, chinstrap, and gentoo penguins have increased in the southwest Atlantic sector since the period of commercial whaling. In a review of the biology of the Southern Ocean, Knox (1994) concludes that evidence for a correlation between whale declines and increased krill predator populations is weak.

D. KRILL FISHERY

The fishery on Antarctic krill began in the 1970s and quickly expanded to annual catches of 300 to 500 thousand tons during the mid-1980s and early 1990s with effort concentrated in the southwest Atlantic sector (Figure 5). Low catches in 1983, 1984, and 1985 coincided with low krill availability and poor krill predator reproductive success at South Georgia (Croxall et al., 1988). The decline in catches after 1992 coincides with political changes in the Soviet Union, which until this time was the principal harvester.

The current fishery operates in the winter around South Georgia and, with the retreat of the sea ice, in the summer around the South Orkney and South Shetland Islands. Overall fishing effort increases as the fishing season progresses from winter to summer, and peak catch levels occur in the summer toward the end of February (Nicol and Endo, 1999). The vicinity of the South Shetland Islands is an especially productive fishing ground and the one most heavily exploited in summer months. Current krill fishing effort is concentrated along the shelf breaks north of the islands where the fishery relies on predictable concentrations of adult krill to support its operations (Agnew and Nicol, 1996). The occurrence of eddies, which are common in this area, are also correlated with krill catch distribution (Makarov et al., 1988; Murphy et al., 1997). Other regions (e.g., to the south of the South Shetland Islands) are dominated

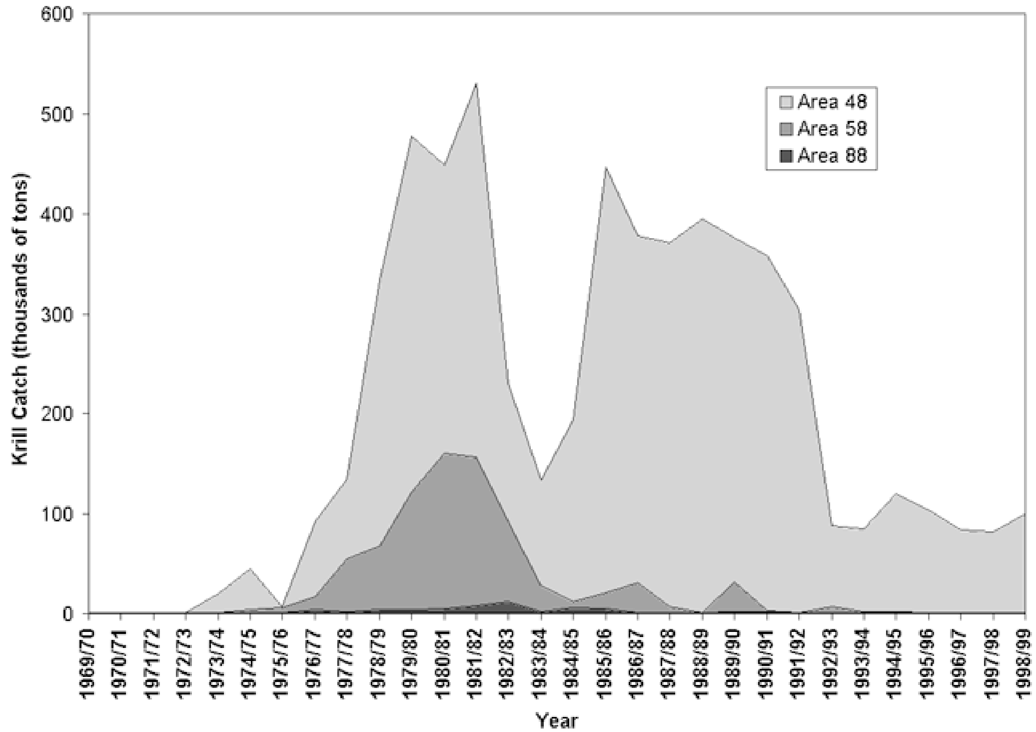

FIGURE 5. Krill catches by year and area. (Source: Convention for the Conservation of Antarctic Marine Living resources, Hobart, Australia.)

FIGURE 6A. Japanese krill trawlers operating off the north coast of Elephant Island, South Shetland Islands, Antarctica. (Photo credit, Roger Hewitt.)

FIGURE 6B. Scientific krill catch aboard the South African R/V *Africana* near the South Orkney Islands. (Photo credit, Roger Hewitt.)

by juvenile krill swarms or low adult krill concentrations and are not economically exploitable at present.

For environmental and logistical reasons, the krill fishery is likely to remain concentrated in the southwest Atlantic sector of the Southern Ocean as opposed to expanding into the Pacific or Indian Ocean sectors. Sea ice in this area recedes dramatically in summer months, exposing the productive shelf break regions and large areas of open water in areas where sizable concentrations of krill may be found (Murphy et al., 1997; Agnew and Nicol, 1996). The Antarctic Peninsula and surrounding areas also experience relatively favorable weather conditions, harbor numerous scientific bases, and are relatively accessible from the tip of South America (transit to Antarctica from Punta Arenas, Chile takes only 3 days, as opposed to 7 to 10 days from South Africa or Australia). Because of the favorable fishing conditions in the southwest Atlantic sector, as well as proximity to supplies, shelter, ports, and potential markets, this region may be viewed as the center of krill fishing operations.

Despite the rather restricted potential for spatial expansion, the krill fishery in the South Shetlands may be far from reaching its capacity (Agnew and Nicol, 1996). Based on a population yield model, CCAMLR has estimated that annual harvests of 4.1 million tons are sustainable from the southwest Atlantic sector, and that as much as 1.6 million tons could be taken from the vicinity of the South Shetland Islands (SC-CAMLR, 1997). Although the estimates of yield have changed with adjustments to estimated biomass, the Scientific Committee has consistently recommended that a precautionary limit to annual harvests of 1.5 million metric tons be set for the southwest Atlantic sector (SC-CAMLR, 1994, SC-CAMLR, 1995, SC-CAMLR, 1997). This is still well above current annual harvests of approximately 0.1 million metric tons.

However, these numbers must be interpreted with caution. The accuracy and current relevance of the krill survey conducted in 1981 that was used to scale the model, as well as the ability of the model to incorporate cyclic environmental variability, are under debate. Furthermore, the krill fishery is concentrated within 150 km of shore during summer months in the South Shetland and South Orkney Islands and runs the risk of interfering with colonies of breeding seals and seabirds (Agnew and Phegan, 1995; Nicol and de la Mare, 1993). Agnew (1992) found that the pattern of fishing near the South Shetland Islands over the period 1988 to 1991 was highly consistent between years, and that 70 to 90% of the total catch between December and March was taken within 100 km of penguin breeding colonies each year. The CCAMLR mandate for maintenance of ecological relationships implies that analysis of krill fishery potential should specifically account for local availability of krill to these predator populations. The current form of the krill yield model does not specifically address interactions between fishing and predator foraging.

In the context of large natural variations in the abundance of krill, it is difficult to determine the effects of fishing on local predator colonies. Fedoulov et al. (1996) note that both research surveys and krill fisheries report major reductions in krill availability in years when the predators do poorly. Croxall et al. (1999) report that the reproductive performance of the krill-eating species monitored at South Georgia (gentoo penguin, macaroni penguin, fur seal, and black-browed albatross) was significantly depressed in years of reduced krill availability, and that associated changes in population sizes of these species were evident (primarily due to adult mortality). In contrast, squid and fish-eating species (grey-headed and wandering albatross) were essentially unaffected by krill reductions. Similarly, Croxall et al. (1988) show that the breeding success of chinstrap penguins is significantly reduced by any delay in the break out of ice in the spring, and hence the onset of krill availability. In addition, they relate major variations in parameters such as breeding success, offspring growth rate, and foraging trip duration to changes in food availability.

A number of modeling studies indicate that krill fisheries may have the potential to impact krill predators. Butterworth and Thompson (1995) developed a "one-way" interaction model in which krill abundance fluctuations impact the predator populations, but not vice versa. Simulations based on this model indicate that the variability in annual recruitment of krill decreases the resilience of predator populations to krill harvesting. Mangel and Switzer (1998) modeled foraging trips of Adelie penguins in order to investigate the effects of a fishery operating near the breeding colony. They predicted that reproductive success would decline with increases in krill catch at a faster rate than adult survival. The expected reductions in offspring and parent survival are mainly determined by how long the fishing season lasts and the capacity for harvest, rather than when fishing begins. The predictions of these models, however, are most sensitive to the assumed residence time of krill within the foraging range of krill predators. The movement of water, and the possible actions of krill to maintain their position, in these hydrographically complex areas are poorly understood.

In their review of krill fisheries, Nicol and Endo (1997) noted that the Antarctic krill fishery is currently held in check by (1) economic and marketing factors relating to high costs and problems in processing and (2) a lack of demand. Most of the krill caught in commercial fisheries is used in aquaculture feed as a source of protein and flesh pigmenting carotenoids (Storbakken, 1988). In addition, the Japanese Antarctic krill fishery (which currently takes a majority of the catch) produces boiled, frozen krill for sport fishing bait and peeled tail meat for human consumption. It is possible that as conventional wild fisheries decline due to overfishing and human population levels continue to rise, there will be a greater demand for abundant species such as krill. Developments in food technology may result in more rapid production of cost-effective krill products for human consumption and, as prices for farm-reared fish increase, innovative technologies may act to promote the use of krill as aquaculture feed. The expansion of the fishery may be encouraged by advances in technology, which make processing more efficient and allow fuller utilization of the catch in a variety of new products, including biochemical extracts, autoproteolytic precipitates, food additives, lipid and other protein concentrates, hydrolytic ensymes, and chitin (Nicol and Endo, 1999). In recent years, companies from India, Canada, the United Kingdom, the United States, Norway, and Australia have publicly expressed interest in exploiting the krill resource. Despite these possibilities and announced intentions, the Antarctic krill fishery has remained level since 1992. Should a market develop for high value uses such as pharmaceuticals, industrial products, and aquaculture feed, the krill fishery may be put on a sounder economic basis and large-scale commercial harvest may resume. Alternatively, the status quo may prevail.

E. ESTIMATING KRILL YIELD

Existent krill management measures, the precautionary catch limits, are derived from a population model referred to as the krill yield model. Development of the model was partially motivated by concerns raised in 1990, when estimates of krill biomass near South Georgia were only 600,000 metric tons and the localized fishery was taking as much as one third of this amount each year (SC-CAMLR, 1990). The krill yield model (Butterworth et al., 1992) is based on a simple approach proposed for fish stocks by Beddington and Cooke in 1983. This approach involves the determination of a factor (γ), the proportion of unexploited biomass that can be caught each year. The essential conditions of this approach are (1) the availability of a single estimate of the resource biomass prior to the initiation of harvest; (2) the assumption that annual recruitment does not fall as the spawning stock size drops; and (3) the evaluation of a potential yield that satisfies a risk criterion to minimize the probability of impairing recruitment (de la Mare, 1994a). With respect to the specific nature of krill and the krill fishery additional modifications allowed for:

(1) strong seasonal effects such as all somatic growth occurring during 3 months of the year; (2) the possibility that the fishing season may not extend throughout the entire year; (3) imprecision of the survey estimate of biomass; and (4) uncertainties in the estimates of biological parameters such as recruitment and natural mortality (SC-CAMLR, 1991; Butterworth et al., 1994).

The population model is an age-structured model that relies on the following information for its catch limit calculations: (1) an initial estimate of the total biomass of the krill stock in an area; (2) an estimate of the rate of natural mortality; (3) a simulation model of krill populations; and (4) an estimate of the interannual variability in recruitment. It has the form:

$$\mathbf{Y} = \gamma \mathbf{B_0}$$

where **Y** is the annual krill yield; γ is the proportion of the biomass that can be caught each year; and $\mathbf{B_0}$ is a measure of the total biomass prior to exploitation.

Year-to-year krill variability is accommodated by a simulation model, which includes random variability in recruitment and is used to calculate a distribution of population sizes both in the absence of fishing and at various levels of fishing mortality. This simulation model is run with varying values for growth, mortality, and abundance drawn at random from defined distributions, allowing for the incorporation of natural variability and uncertainty in measurement. The resulting distributions are used to determine γ. The greater the value of γ (the proportion of the biomass that can be caught each year), the higher the permitted fishing intensity.

CCAMLR has developed a three-part decision rule for determining the value of γ:

1. Choose γ_1 so that the probability of the spawning biomass dropping below 20% of its pre-exploitation median level over a 20-year harvesting period is 10%
2. Choose γ_2 so that the median level of krill spawning biomass in the exploited stock in the over a 20-year period is 75% of the preexploitation median level
3. Select the lower of γ_1 and γ_2 as the level of γ for the calculation of krill yield (SC-CAMLR, 1991)

The first two decision criteria correspond to values of γ: γ_1 concerns the probability that krill spawning biomass will drop below a sustainable level, and γ_2 attempts to address the needs of the krill predators. In an ecosystem context, these criteria are followed to ensure that there is not only a sustainable level of krill production, but also that the needs of all of the predators are safeguarded (Everson and de la Mare, 1996). Because detailed modeling on how the krill fishery might impact krill predators has yet to provide reliable quantitative results, an *ad hoc* approach is utilized in determining γ_2. Specifically, criterion 2 defines a value for γ where the minimal biomass is 75% of the prefishing level; the 75% level is chosen as the midpoint between taking no account of the needs of predators (biomass = 50% of the prefishing level) and providing complete protection for the krill feeding animals (biomass = 100% of the prefishing level). Once criteria 1 and 2 have been established, the lower of the two values of γ is selected (SC-CAMLR, 1994).

The other critical parameter used in this model ($\mathbf{B_0}$, the preexploitation level of krill biomass) was derived from the results of the FIBEX surveys conducted in 1981. After adjusting for technical problems in the original collection and interpretation of acoustic data (Trathan et al., 1992; Tathan and Everson, 1994), $\mathbf{B_0}$ was set at 15.1 million tons in the Southwest Atlantic sector; this resulted in $\mathbf{Y}$ = 1.4 to 2.1 million tons and the recommendation of a precautionary limit of 1.5 million tons (SC-CAMLR, 1991). More recently, the krill biomass estimates from the FIBEX data have been revised to 35.4 million tons with $\mathbf{Y}$ = 4.1 million tons (SC-CAMLR, 1993; SC-CAMLR, 1994). Considering that the current fishery was relatively small, and that there was little evidence for its expansion the Scientific Committee recommended that the precautionary limit remain at 1.5 million tons and the Commission agreed.

Additional adjustments to the krill yield model may be necessary to ensure continued production of reliable and sustainable precautionary catch limits on an area-wide scale. The outputs from the simulation model depend on a variety of biological parameters, which include age-at-sexual maturity, age-at-recruitment to the fishery, and krill natural mortality rate, and are more sensitive to some parameters than others. Specifically, the parameter to which these outputs are most sensitive is the extent to which krill recruitment fluctuates from year to year (Butterworth et al., 1994). Initially, little more than best guesses were available for krill recruitment values. In recent years, however, input from analyses of length frequency data from research surveys, from which estimates of proportional recruitment can be obtained, has reduced uncertainty and improved the precision of the model (Butterworth et al., 1994).

Yet despite the improved precision, questions remain. Annual research surveys have produced local estimates of krill density and proportional recruitment in the southwest Atlantic sector that show wide variations on seasonal, annual, and decadal scales (SC-CAMLR, 1998). These results raised concern over the model's ability to account for the true range and multiyear correlation of recruitment variability. Analyses of research net samples obtained in the South Shetland Islands indicate a decline in krill abundance from high levels in 1977 to 1983 to low levels in 1985 to 1994 (Siegel and Loeb, 1995; Loeb et al., 1997; Siegel et al., 1997). Concordances among environmental indices, reproductive performance of krill predators, and acoustic surveys for krill obtained near South Georgia in the South Orkneys and the South Shetland Islands suggest that these trends may be consistent across the entire southwest Atlantic sector (SC-CAMLR 1998, Report of the Workshop on Area 48).

Because annual krill recruitment varies naturally, the biomass of the krill population fluctuates even in the absence of exploitation. Thus, this biomass could be above or below its median level at the time a preexploitation survey takes place. The krill yield model takes the existence of these fluctuations into account in its calculations. However, if extra information becomes available that allows estimation of the trend and extent of the difference between the current krill biomass and its median preexploitation level at the time of the original survey, the krill yield model could be refined and provide an improved estimate of potential yield.

With regard to the management of the krill fishery, CCAMLR has defined two primary objectives: (1) ensuring the viability of the Antarctic krill population (overall krill biomass) and (2) maintaining a level of near-shore krill biomass adequate to fulfill the foraging needs of land-breeding krill predators (SC-CAMLR, 1991; Everson and de la Mare, 1996). Revisions to the krill yield model in response to new information on the variability of recruitment and abundance may be satisfactory to address the former objective. However, the protection of regional krill populations may require modification of the area-wide application of the krill general yield model as well as the development of more specific ecosystem models that account for spatial and temporal variations in the availability of krill to predators.

Krill are not evenly distributed throughout southwest Atlantic sector, with some areas containing higher concentrations than others. The general pattern of krill distribution in this sector is presumed to be determined by transport via the Antarctic Circumpolar Current. Considerable debate has ensued in the Scientific Committee as to whether, and if so how, the effects of immigration and emigration of krill from one region to another during the course of a year should be taken into account in the development of management measures (Everson and de la Mare, 1996; SC-CAMLR, 1990, 1991). Yet due to the high level of uncertainty on the regional characteristics of krill populations and the ensuing difficulties in adjusting for the effects of transport, CCAMLR was unable to agree on a way to set smaller-scale catch limits for individual Subareas 48.1, 48.2, and 48.3 (Watters and Hewitt, 1992).

The adoption of the area-wide approach also raised concerns that geographically concentrated removal of the total allowable catch might cause local overfishing and adversely impact local predator populations. Other than the operational rule that the expected median krill biomass remain at 75% of the preexploited level, CCAMLR has not specifically addressed the effects of concentrated fishing on local land-breeding predator populations. Concentrated fishing may have a disproportionate impact on adjacent colonies, reducing or even eliminating their viability. One result could be the reduction of genetic diversity among subpopulations of land-breeding penguins. Before these potential impacts can be evaluated, it will be necessary to define the possible limits of relationships between krill, land-breeding krill predators, and the fishery. Initial models and analyses include those by Butterworth and Thompson (1995), Agnew and Phegan (1995), Ichii et al. (1996), and Croll and Tershy (1998). In the meantime the Commission has agreed to impose additional precautionary measures in a particular Subarea if the catch from that Subarea exceeds 620,000 tons in a single fishing season (SC-CAMLR, 1991).

As more data become available and the uncertainty associated with input parameters is reduced, it is expected that CCAMLR will continue to adopt refinements to the krill yield model by adjusting the value of γ to better avoid recruitment overfishing. To this end, CCAMLR members have been encouraged in recent Scientific Committee meetings to look for long-term trends in krill abundance and recruitment, and to suggest refinements in the calculation of krill yield (SC-CAMLR, 1996). Furthermore, concerns over the reliability and current relevancy of the FIBEX survey (SC-CAMLR, 1995) have prompted CCAMLR to sponsor a large-scale near-synoptic survey of krill in the southwest Atlantic sector to take place in the summer of 1999/2000. The intent of this survey is to replace the 1981 FIBEX biomass estimate with an updated value of $\mathbf{B_0}$ and its variance (SC-CAMLR, 1997). Given the uncertainties associated with the krill yield model, the Scientific Committee has agreed not to revise the current precautionary catch limits until after the year 2000 survey is complete and more information on krill biomass and recruitment variability is available. Of equal importance to updating the krill yield model is the development of ecosystem models detailing the relationships between small-scale krill availability, land-breeding krill predators, and the krill fishery. While the general krill population does not face great risk of being overfished on a large scale, krill aggregated on shelf breaks near breeding predator colonies are currently the focus of fishing efforts. If warranted, additional conservation measures could be adopted with the objective of redistributing fishing effort, both temporally and spatially, so as to reduce the interaction between krill predators and krill fishing.

IV. STRATEGIC PLANNING FOR THE FUTURE

The development of the Antarctic krill fishery so far has gone against the more consistent worldwide trend of overcapitalization and overexploitation in the pursuit of large-scale fisheries (Ludwig, 1993). This has benefited CCAMLR in that it has provided time to develop procedures with which to address its mandate to maintain the integrity of ecological relationships among harvested and dependent populations. The terms of CCAMLR also require proactive rather than reactive measures to prevent change resulting from human fishing activities. No precedent yet exists for the successful application of an ecosystem approach to the management of a world fishery and CCAMLR faces a difficult task. This task is aided by the current lack of economic incentives to harvest krill, but hindered by scientific, economic, and political uncertainties.

Although CCAMLR emerged too late to prevent the overfishing of many of the fin-fish populations, member nations have succeeded in setting precautionary catch limits intended to avoid the overharvesting of krill in the case of rapid fishery expansion. However, current management measures may not be sufficient to ensure adequate prey on local or regional scales to land-breeding krill predators, particularly during years of reduced krill availability. Concerns regarding critical parameters of the krill yield model and the continued debate over the model's area-wide application suggest that the current CCAMLR approach may not be adequate in the case of increased and/or concentrated fishing pressures. The importance of defining the nature of krill recruitment variability and its dependence on environmental variability is increasingly recognized, as is the need to incorporate this information into management procedures. Scientific uncertainties limit understanding of these factors, however, and thereby hinder efforts to include them in a revised and improved methodology for catch limit determination.

As CCAMLR improves its management tactics, it must also take into account updated political and economic forecasts. At present, CCAMLR may be considered an arena for experimentation on ecosystem management. Fishing effort is limited, the current economics of the fishery do not favor expansion, and the krill biomass is considered large relative to the harvest. It may be advantageous for CCAMLR member nations to bolster their resource conservation images by supporting and sustaining this experiment (Vicuna, 1996). Under these circumstances the consensus-based management procedure remains harmful to none and therefore workable. However, should major breakthroughs occur in the demand for krill, for example, its use in aquaculture or pharmaceuticals, the balance may change. Both claimant states and other fishing nations may begin to invest in the krill fishery, the consensus procedure will give fishing nations eager to preserve their fishery potential a valuable veto, and scientifically defensible conservation measures may become more difficult to pass.

A. FUTURE SCENARIOS

The most effective path for CCAMLR to follow in the future will depend on the range and likelihood of situations it faces in the future. In their essay on fisheries management Lane and Stephenson (1998) argue that all potential scenarios, both desirable and undesirable, should be considered in the evaluation of decision alternatives. Decision alternatives for CCAMLR will depend primarily on four factors: (1) the development of the krill fishery; (2) the pattern of krill population variability; (3) the degree to which scientists are able to predict and accommodate this variability; and (4) political considerations such as the requirement for consensus.

Considering these factors, the spectrum of potential scenarios for CCAMLR may be defined by a matrix (Table 2). The matrix is constructed along two vectors of uncertainty: (1) development of the krill fishery in the southwest Atlantic sector (e.g., status quo, moderate, or rapid) and (2) the dominant nature of krill variability in this sector (e.g., interannual, decadal scale, or long-term trend). In the following paragraphs, the management implications of the six states of uncertainty are identified. The likelihood of various future scenarios resulting from the intersections of these states of uncertainty is discussed and the most appropriate actions for CCAMLR are identified.

TABLE 2

Matrix of Future Scenarios Along Two Vectors of Uncertainty: The Future Development of the Krill Fishery and the Nature of Krill Population Variability

	Variable 1: Status Quo- small-scale fishing effort (50,000-200,000 metric tons)	**Variable 2**: Mid-range fishery expansion (200,000-800,000 metric tons)	**Variable 3**: Rapid fishery expansion (To 1.4 million metric tons or higher)
Variable 4: Short-term variability (Seasonal to interannual)	Scenario 1	Scenario 2	Scenario 3
Variable 5: Decadal scale variability (10's of years, regime shifts)	Scenario 4	Scenario 5	Scenario 6
Variable 6: Long-term declining trend (10's-100's of years)	Scenario 7	Scenario 8	Scenario 9

The first three states of uncertainty relate to the future development of the krill fishery:

(1) No change in the Development of Fishery: Fishery continues at a current level (50,000 to 200,000 tons per annum). Only a handful of nations are involved in the fishery, and the fishing effort remains concentrated near the shelf breaks surrounding the South Shetland and South Orkney Islands during the summer and South Georgia in the winter.

Management Implications: At the current level of fishing pressure krill populations are probably not threatened because localized removals may be replaced by transport of krill into the area. However, concentration of fishing activity near shelf-break areas could impact the reproductive success of land-breeding predator populations. In light of the extent of natural variability in krill abundance, it is possible that predator reproductive success is substantially impacted in years of low krill biomass independent of the fishery. In addition, spatial variability in krill concentrations governed by changes in current patterns adds to the vulnerability of predator populations. In any given season, land-breeding predator populations might experience near-shore declines in krill availability due only to relative shifts in abundance. These additional concerns require that CCAMLR be attentive to localized regions of higher predator sensitivity and attempt to regulate fishery activities accordingly.

(2) MidRange Fishery Expansion: Fishery returns to mid-range levels (200,000 to 800,000 tons per annum), similar to those reached in the 1980s. The current precautionary catch limits are still not reached. New nations begin to enter the fishery as new krill products make the fishery more profitable. Fishing effort remains concentrated near the shelf breaks surrounding the South Shetland and South Orkney Islands during the summer and South Georgia in the winter.

Management Implications: If the krill fishery increases to moderate levels the krill population in the southwest Atlantic sector will mostly likely not be adversely affected under the assumptions of the current yield model. The protection of local krill populations for krill predators should remain the primary concern, especially in years of low krill abundance. Heightened or concentrated fishery pressure should be closely monitored and controlled. Periodic surveys of krill predator populations and studies of the impacts of environmental change on both krill and higher trophic levels should also be management priorities. The ability to distinguish the impacts of fishing from the effects of environmental forcing would help in the development of appropriate fishery control measures and precautionary catch limits. Unfortunately, it may not be possible to distinguish the impacts of a fishery from those of environmental variability with only moderate fishing effort. In order to unambiguously observe and quantify fishery impacts intense fishing pressure may be necessary. This presents a difficult management dilemma: in order to better manage the fishery the impacts must be quantified, yet fishing effort may need to be substantial before this is possible. This also puts additional emphasis on the importance of continued monitoring so as to establish the extent of natural variability in the availability krill to predators and their responses.

(3) **Rapid Fishery Expansion:** The development of efficient processing technology combined with the emergence of valuable krill products promotes rapid development of the fishery to the precautionary catch limit (1.5 million tons per annum) or beyond. Fishery centers in the South Shetland and South Orkney Islands in summer months and South Georgia during winter months, but may begin to expand out of these areas due to crowding and competition.

Management Implications: Although an annual krill yield of 1 to 3 million tons may still not be a cause of immediate concern for the krill population in the southwest Atlantic sector under the assumptions of the current yield model, rapid expansion of the fishery close to the shelf break areas could introduce strong competition for locally limited krill resources resulting in adverse impacts to land-breeding krill predators. Obtaining an accurate baseline of krill variability and quantifying the responses of krill-dependent populations to this variability using fine-scale models may allow managers to better discern the additional affects of the fishery. If declines in predator populations can be attributed to increases in local fishing effort, additional controls on the fishery may be justified. Dramatic increases in fishing pressure may also lead to vessel competition and overcrowding in the productive shelf-break areas where krill congregate. In this case, the fishery may begin to expand spatially or temporally into adjacent regions around the Antarctic continent or other seasons, to the extent that economic gains continue to be realized. Spatial expansion of the fishery will need to be matched by extension of scientific research into target regions in order to account for specific local conditions in management measures. Seasonal expansion of the fishery will also require additional modification of the krill yield model. The political climate may change as well. Sufficient financial motivation could cause claimant states to begin enforcing rights to their Exclusive Economic Zones. CCAMLR's ability to establish management provisions could be complicated by competing economic interests. High levels of scientific uncertainty could be again used as an excuse to hinder consensus agreement on conservation measures. The best route for CCAMLR would be to establish management provisions before the fishery expands with the understanding that precautionary levels may be adjusted as knowledge increases. Once fishing interests begin to invest in fishery capital, they will be reluctant to incur economic losses and relaxing overly protective controls in the future may be far easier than strengthening weaker conservation measures.

The second three states of uncertainty relate to the nature of krill population variability:

(4) Short-Term Krill Variability: Krill recruitment and biomass fluctuate around a mean level, varying from 1 year to the next in response to external forces such as the environment and the fishery. The most likely environmental influences on short-term variability are annual fluctuations in sea ice development and changing current patterns, both of which impact krill population growth and dispersion.

Management Implications: In this case, the critical issue is the incorporation of accurate levels of natural variability (both temporal and regional) into the krill yield model, or additional models, which would allow for reliable and sustainable precautionary catch limits despite high levels of interannual change. Recent estimates of the magnitude of krill recruitment variability appear to exceed those accounted for in the krill yield model, and the original estimate of $\mathbf{B_0}$, resulting from the 1981 FIBEX data, might not accurately reflect the current status of the krill population in the southwest Atlantic sector. Thus, if natural interannual variability is a primary influence on krill populations, CCAMLR's chief concern must be the regular assessment and revision of the krill yield model in response to increases in scientific understanding of the scales of interannual variability in recruitment and biomass parameters. These efforts will require regular, large-scale monitoring programs of krill (including regularly updated biomass estimates), krill predators, and the Antarctic physical environment. In addition, multivariate models that describe interactions between these components may allow the signals of natural variation to be separated from impacts of the fishery.

(5) Decadal Scale Variability: Krill recruitment and biomass experience multiyear cycles or decadal scale shifts in mean levels. One regime of higher than average levels may be followed by an extended period of time of lower than average levels, the shift most likely being caused by changes in ocean physics. Random, natural variability continues to be superimposed on these shifts in average krill recruitment and biomass from one regime to the next.

Management Implications: Detecting the occurrence and impacts of regime shifts requires comprehensive monitoring of physical parameters and identification of corresponding changes in biological populations. These efforts should complement a historical-descriptive approach (Francis and Hare, 1994) in which a model is developed and supported by historical scientific evidence from disparate sources. If regime shifts are shown to be occurring, CCAMLR's first step should be the thorough revision of the krill yield model to reflect current conditions and levels of variability. Once the impacts of the current regime on biological populations are accounted for in reliable management measures, regular monitoring of environmental variables may help to detect the beginning of a shift to a new regime. In other marine systems, overfishing has been known to convert population declines of target species resulting from regime shifts into commercial collapse and may increase the rate and frequency with which these shifts occur (Steele and Henderson, 1984; Steele, 1998). Thus, appropriate management action should be taken as soon as a regime shift is expected or recognized. For example, as these shifts are likely to alter the baseline krill population mean around which biomass fluctuates, the average level in the krill yield model may need to be revised in order to better track changes in the ecosystem. Changes in regional patterns of krill distribution resulting from a regime shift may also impact predators and, if possible, should be accounted for in fine-scale predator-prey models. Re-analyzing long-term records of environmental variables such as atmospheric pressure, temperature, and sea ice in the search for past trends may offer clues to the patterns, signals, and implications of regime shifts. CCAMLR should be aware of the possibility of rapid, large-scale environmental change, and should establish a set of management plans corresponding to an array of possible scenarios in case a substantial decrease (or increase) in krill abundance is predicted.

(6) Long-Term Declining Trend: Krill biomass and recruitment are decreasing slowly but steadily in the southwest Atlantic sector. This trend is most likely linked to an increased frequency of years with below-average seasonal ice cover, which in turn is directly connected to a warming trend experienced in the region since the 1940s. Random, natural variability continues to be superimposed this long-term trend.

Management Implications: If krill populations are undergoing a long-term decline, CCAMLR must ensure that fishing does not enhance this trend or additionally burden predators in the long run. In the short run, krill population changes are likely to mostly reflect natural interannual variation that may be accounted for by revising the krill yield model. However, in its present state the krill yield model only accounts for random parameter variability about a mean value, not for any systematic changes in krill recruitment or biomass. Thus, quantifying and factoring the long-term decline into management models will be of critical importance if precautionary measures are to accurately reflect current as well as future realities. As krill biomass continues to decline, management measures will need to be adjusted to protect the resource for both predators and the krill stocks themselves. The analysis of current links between regional warming, sea ice trends, and krill recruitment may provide a starting point for the quantification of any long-term decline and its incorporation into management plans. In addition to the rate of change, attention should be focused on whether this is a regional phenomenon or more widespread, and if it is regional whether krill stocks in the southwest Atlantic sector will be replenished by transport from other areas. Revisions to the krill yield model may be able to provide a series of precautionary catch limits for future years that account for krill declines, allowing the fishery to plan for a future with reduced krill availability. As in previous scenarios, it will also be necessary to develop additional methods of accounting for the regional impacts of krill declines or fishing on krill predator populations. Extensive monitoring will be the key to the detection of these local or regional adverse effects on krill or their predators from a long-term krill decline that may be augmented by a fishery.

While any one of the trajectories for the development of the krill fishery excludes the other two possibilities, the three temporal scales of krill variability are not mutually exclusive. All three scales are likely to contribute to the overall pattern of variability, although the relative contribution of each is less certain. Natural short-term variability due to seasonal changes, environmental influences, or simple random fluctuations is inherent in any natural system. Decadal scale regime shifts have been demonstrated in many other marine systems through marked changes in physical conditions and in the abundance of fish stocks, even before severe overfishing has occurred (Cushing, 1981). Observations of multiyear cycles in the extent of sea ice development in the Antarctic Peninsula area (Stammerjohn and Smith, 1996), an 8-year cycle in fast ice and air temperature at the South Orkney Islands (Murphy et al., 1995), and an eastward moving circumpolar wave of sea surface temperature and wind anomalies with 4 to 5 year period (White and Peterson, 1996) suggest that regime shifts in the Antarctic marine environment are a governing force. Finally, longer-term krill declines superimposed on interannual and decadal variability are probable as a consequence of warming trends in the Peninsula region, the associated decreases in annual sea ice development, and the reliance of krill on the sea ice habitat for successful overwinter survivorship and subsequent recruitment (Loeb et al., 1997). Evidence for multidecade regime shifts in sea ice extent is also apparent from historical whaling records (de la Mare, 1997).

Despite of the above caveats, the most appropriate directions for CCAMLR management of the krill fishery depends on both the development of the krill fishery and the nature of krill variability. These factors may interact in numerous ways, resulting in several possible future scenarios (Table 2). In the best case (Scenario 1), krill populations would vary with predictable range about a steady mean and the fishery would remain minimal. This would allow for the incorporation of accurate parameters into the krill yield model, the subsequent production of reliable precautionary catch limits, and the minimization of human and krill predator competition for the krill resource. In the worst case (Scenario 9), krill populations would undergo a long-term decline in response to environmental forcing, concurrent with dramatic fishery increases resulting from the emergence of novel krill products. The krill yield model in its present state does not allow for directional change in the estimate of $\mathbf{B_0}$ and would require revision. In addition, localized models of trophic interactions would be necessary in order to rationalize conservation measures designed to protect the foraging needs of predators. At the same time, strong economic incentives would elevate fishing activity in the krill-containing shelf-break areas near critical breeding grounds and limit the willingness of fishing nations to agree to conservation measures. However, neither the best nor the worst case is most likely to become reality. More likely, the future will include gradual but steady increases in fishing pressure as new products emerge, combined with some overall level of regional krill variability comprised of trends on all three scales, interannual, decadal, and long term.

In addition to the likelihood of each scenario, attention should also be directed toward the apparent risks. For example, while the probability of a rapid fishery expansion combined with dramatically decreasing krill populations is low, the potential of this combination to induce harm is great and must be considered accordingly.

B. A STRATEGIC PLAN FOR CCAMLR

In the foregoing discussion of management implications several actions were repeatedly indicated as being appropriate. These include: (1) updating the parameters in the krill yield model to more accurately reflect observed distributions; incorporating adjustments to the model for shifts in mean abundance, year-to-year serial correlation in recruitment, long-term trends in abundance, seasonal, and spatial shifts in fishing effort; (2) Quantifying, monitoring, and, if necessary, controlling increased or concentrated near-shore fishing pressure; (3) monitoring the worldwide market for euphausiid-derived products and the development of the fishery on Antarctic krill; describing current fishing tactics and their evolution as the fishery expands and/or the dispersion patterns of the resource change; (4) monitoring krill abundance, demography, and availability as well as krill predator responses to variations in their prey field on regional scales; monitor environmental variability postulated to affect secondary productivity; (5) development of fine-scale models that describe the relationship between krill availability and foraging by land-breeding krill predators; development of linked models that relate provisioning during the breeding season to reproductive performance, population demographics, and population abundance; (6) development of open-ended ecosystem models that include multiple trophic levels and variable environmental influences; and (7) establishing periodic krill surveys to reestimate the krill biomass in the southwest Atlantic sector.

Fortunately, CCAMLR is already implementing many of these options. A multination, multiship survey of krill throughout the southwest Atlantic sector has been organized by CCAMLR and was conducted in January 2000. The survey was designed to provide a revised estimate of $\mathbf{B_0}$ as well as examine the variation in krill demographic parameters across the sector. As part of its ecosystem monitoring program (CEMP), CCAMLR encourages national programs designed to monitor the status of krill, krill predators, and their environment in more localized areas. The continuation and expansion of these efforts will lead to better descriptions of critical processes and more robust models. This in turn may generate adjustments to the krill yield model or the development of complementary models to include localized predator demand and the impacts of environmental variability.

However, given the complexity of the system and the range of scientific uncertainty, the information requisite for adapting or revising the krill yield model to account for spatial variations in predator demand and temporal variation in environmental influences is not likely to be available in the near future. While no evidence exists yet that the fishery has an effect on krill predators, the risk remains, especially if the fishery begins to expand, and should be taken into account. All evidence to date suggests that the locales of highest fishery activity coincide spatially with shelf-break regions adjacent to productive predator feeding grounds and seasonally with critical summer breeding months. Several studies have addressed competition between the fishery and natural krill predators in the analysis of fishery control mechanisms. Watters and Hewitt (1992) examine a range of control options and conclude that those least detrimental to the krill fishery are the establishment of protective zones around islands and periods of curtailed fishing during critical breeding periods. Similarly, Agnew and Marin (1994) consider a number of scenarios involving closure of zones around South Shetland Islands and Elephant Islands and conclude that closing various near-shore zones in alternate years could provide predators with a necessary respite from fishery competition.

The management actions outlined above depend, either for their development or their verification, on an observation system designed to monitor various processes in the pelagic ecosystem. They also imply that a management scheme is in place that will dictate responses to these observations. This is in concert with discussions ongoing in the Scientific Committee in support of efforts to define a system of "ecosystem monitoring and management" (e.g., SC-CAMLR 1995).

As a contribution to these discussions, we propose a three-pronged strategy for CCAMLR with regard to the future management of the Antarctic krill fishery. The three elements would include: (1) identification and monitoring of key processes governing krill abundance and dispersion; (2) elaboration of resource management rules based on indicators of key processes; and (3) research activities designed to reduce uncertainty, monitor performance, and improve the management scheme. Such a strategic plan, outlined first in broad terms and refined through discussions among CCAMLR members, may provide structure to a diverse range of activities conducted by national programs in support of CCAMLR objectives. It may also have the effect of highlighting critical issues in need of immediate attention, encouraging discussions with regard to CCAMLR's preparedness for future scenarios, and refocusing attention on the system rather than individual components. The three elements are briefly outlined below, including some example initiatives that could be pursued within each of the elements.

1. Process Monitoring

This element can be broadly defined as the identification, monitoring, and modeling of any process (physical, biological, or human) that affects the population dynamics of Antarctic krill, the viability of krill predators, and the nature of the fishery on krill.

CCAMLR's current management objectives with regard to the krill fishery in the southwest Atlantic are to (1) preserve the viability of the krill population, and (2) preserve adequate prey for krill predator populations. Processes that should be monitored in support of these objectives are those that influence population growth of krill and krill predators in the southwest Atlantic sector. With regard to krill, they are those processes that control recruitment and transport. With regard to krill predators, it is those processes that control reproductive performance, juvenile and adult survival, and dispersal.

Such activities, of course, will evolve as we understand more about the krill-centric system and refine our ideas as to the critical processes. Some processes will be incorrectly identified or result in exerting less influence than originally thought. Other processes may assume more importance or depend on additional factors than originally specified. As knowledge of the system evolves it will be advantageous to articulate current hypotheses regarding the controls on secondary and tertiary production and what should be monitored in order to track or predict change. The same can be said regarding the development of products by man that make use of euphausiids, the expansion of the fishery, changes in fishing and processing technology and corresponding changes in fishing tactics. Thus, an important output from this element of the strategic plan would be a periodic and coherent statement of what should be monitored and why.

Such statements could be used to defend and/or enhance ongoing monitoring and modeling activities by member nations conducted in support of CCAMLR objectives. They could be used to highlight gaps in the monitoring program and encourage other CCAMLR members to initiate research activities. They could also be used in a critical examination of monitoring activities that when initiated appeared to be important, but in light of current understanding are less so. Thus, resources released could be directed toward more critical monitoring.

Once CCAMLR has identified which processes should be monitored, another set of activities can be defined. These include the identification of proxies or indicator variables, the elaboration of standard methods and survey designs, the formulation of indices derived from field measurements, identification of correlates and/or leading indicators that may be used as simple prognosticators of future trends, and development of methods for aggregating indices so as to make qualitative statements regarding the status of the system.

Ultimately, the results of monitoring need to be abstracted in order to address a variety of questions. Sampling designs, measurement errors and the estimated range of natural variability should be examined. Parameters in the krill yield model need to be updated. Foraging tactics and breeding success of krill predators in response to variations in the availability of their prey need to be characterized and parameterized. Ecosystem models, which account for environmental influences, localized predator foraging, and transport of krill in and out of the system, should be developed in order to test assumptions of trophic exchange rates and mass balance. More focussed models should be developed in order to test assumptions regarding critical processes and their influence.

The extent and adequacy of the existing CCAMLR ecosystem monitoring program (CEMP) is dependent on national programs conducted by member states. While these efforts are commendable, there is room for considerable improvement. The number of predator monitoring sites and their geographic dispersion could be increased so as to measure variability (and concordance) over a range of spatial scales. The number of predator species, indices, and colonies observed at a single site could be increased so as to quantify the effects of additional factors and better examine measurement errors. Pelagic predators such as baleen whales and crabeater seals should be considered.* The spatial extent of regional surveys for krill could be increased in order to detect geographic variations in demographic structure. The frequency of sector-wide surveys of krill could be increased (the CCAMLR 2000 survey in the southwest Atlantic sector will be only the second survey across this area

* This may be accomplished through collaborative research programs with members of the International Whaling Commission (IWC), the Convention for the Conservation of Antarctic Seals (CCAS), and the Scientific Committee for Antarctic Research (SCAR).

in 19 years). Remote sensing techniques could be employed to monitor the intensity and position of the main eastward current flow across the southwest Atlantic sector as well the extent of fronts, meanders, and eddies in the general current flow.

In addition to enhanced monitoring, several other questions could be considered:

- Do variations in recruitment control the size of the krill population? Although available evidence suggests that this is the case, population trajectories that utilize observed recruitment values and reasonable assumptions regarding natural mortality do not match observations of krill abundance over the entire range of the time series (SC-CCAMLR, 1998). Sampling problems may account for some of the discrepancy, but it may also be possible that changes in predator demand, particularly at low levels of krill abundance, may sufficiently alter natural mortality so as to control population size.
- How discrete is the krill stock in the southwest Atlantic sector? It is very likely that substantial immigration occurs from the Bellingshausen Sea, southwest of the South Shetland Islands, and from the Weddell Sea, south of the South Orkney Islands, and emigration occurs to the east of South Georgia. It is also likely that krill do not redistribute themselves freely throughout the southwest Atlantic sector and that krill in each of the Subareas result from different mixtures of krill from various sources. These circumstances may be easier to accommodate if the processes that control krill reproduction and larval survival vary similarly across all sources. However, a description of stock structure and its year-to-year variation may be necessary to interpret changes in krill abundance that cannot be explained by changes in recruitment and/or mortality (both natural and fishing).
- To what extent does reproductive performance and breeding success regulate krill predator populations? A decrease in the size of several colonies of chinstrap and Adelie penguins at a single site in the South Shetland Islands has been observed over the last 20 years. These changes do not appear to be caused by reduced reproductive success, but rather the survival of fledglings during their first 1 to 3 winters at sea (Wayne Trivelpiece, personal communication). This would suggest that availability of krill during the summer breeding season may not be as limiting to penguin populations as the wintertime availability of krill. This also has

implications for the CCAMLR predator monitoring program: at sites with small variations in reproductive success relative to krill availability it may be more sensible to concentrate on studies of penguin demographics and adult survival.

- What are the effects of pelagic krill predator populations such as baleen whales and crabeater seals? These are important pieces of information if we aim to completely specify the krill-centric ecosystem. It may be possible to make gross estimates of consumption, based on surveys of the abundance and distribution of pelagic predators, in order to gauge the magnitude of the effects. However, unlike land-breeding krill predators, pelagic predators are able to move with their prey and their influence during any particular time period may be more difficult to quantify.

2. Management Decision Rules

This element can be broadly defined as the elaboration of management actions triggered by critical values of process indices.

Under the current CCAMLR management scheme for the krill fishery, decision rules have been established to set γ, the portion of the unexploited biomass that may be harvested. The two-step rule aims to protect the krill population as well as the food supply to natural krill predators. The rule, however, is based on an abstract model of a freely distributed krill population with homogeneously distributed predation pressure and randomly determined recruitment. These assumptions were necessary in the absence of better information, but as our understanding of the natural history of krill is improved it may be possible to add decision rules based on the monitoring of critical processes.

As more is understood regarding the hydrographic processes that determine the transport, mixing and geographic dispersion of krill, or the spatial and temporal distribution of predation pressure on the krill resource, or the factors that influence krill reproduction and survival of young, indices may be derived that are sensitive to these processes and incorporated into rules governing the distribution of fishing effort and the allowable harvest. As an example, the total allowable harvest of krill may be adjusted depending on the expected recruitment of age-1 animals, which in turn may be indexed by a combination of environmental and biological variables. The distribution of fishing effort may be adjusted as a result of monitoring leading indicators of hydrographic regimes, which in turn influence the availability of krill to land-breeding predators.

The health of land-breeding predator populations is as important to the success of CCAMLR management as is the status of the resource. Indices may be derived that are sensitive to the processes that control the reproductive success of land-breeding krill predators, the survival and dispersion of juveniles after fledging, and the survival of adults during the nonbreeding period. Management rules that are designed to divert fishing effort away from vulnerable populations at particular locales and/or time periods could be based on such indices. As an example, the harvest allowed near particular colonies of breeding penguins may be adjusted depending on the expected availability of food to just-fledged juvenile birds, which in turn may be indexed by a combination of hydrographic variables and measures of the intensity and timing of spawning by adult krill. As more is learned about the wintertime distribution of adults and the factors that influence their survival, indices may be derived and management rules elaborated that control the harvest of krill during the nonbreeding seasons such that the competition between fishing fleets and adult birds at sea is reduced.

Management decision rules must also be sensitive to developments in the human use of euphausiids and associated changes in the fishery on Antarctic krill. At the current level of harvest management rules may not have a large impact on fishing activities, but as the fishery becomes more capitalized and/or the resource declines or predator populations show signs of stress, regulatory rules will come into conflict with fishing interests. Ideally, critical processes, the appropriate indices with which to monitor them, and management decision rules based on these indices will be elaborated ahead of the developing fishery. With a rationale firmly established, the management scheme will be less vulnerable to criticism and the fishery will develop in reaction to the established management rather than the reverse. Monitoring worldwide demand for euphausiids, the diversion of capital into krill fishing vessels, the development of processing technology and fishing tactics is necessary in order to ensure that the development of management stays ahead of the development of the fishery.

In addition to the elaboration of management decision rules, other strategies could be considered:

- **Experimental fishery**. The monitoring of krill and krill predator populations as they respond to both the fishery and the environment is essential to reducing scientific uncertainty and strengthening management measures. If expanding fishing pressure remains diffuse or highly sporadic, it may be difficult, however, to separate fishery impacts from natural interannual or long-term variability. Under these circumstances it may be advisable to manage the growing fishery in an experimental fashion, with the intention of enhancing the understanding of fishery impacts. For example, CCAMLR might convince fishing fleets to target their efforts in specific areas (at least in the early years), so that impacts on nearby predator populations could be studied. Although this approach might unfairly concentrate fishery impacts on certain predator populations, it could provide valuable insights on the responses of predators to fishing pressure, which may benefit all predator populations in the long run. A flexible experimental management scheme, especially while fishing pressure remains low, could sharpen understanding of the ways in which the fishery impacts the krill-centric ecosystem and result in more focused management rules.

- **Adaptive management**. Elaborating additional management decision rules based on improved monitoring will take time. In the meantime, considering that the krill population may be experiencing a consistent decline or a regime shift to a substantially different biomass, or that fishing pressure near predator colonies may intensify before controls are in place, it may be advisable for CCAMLR to develop flexible management protocols that are adaptable as environmental, krill population, and fishery development trends become more apparent. One option might involve devising a range of management steps to be selectively enforced in years of reduced krill availability. For example, an indication of below average sea ice extent or low krill recruitment could trigger the activation of more stringent management controls or precautionary catch limits. If observed, these activation criteria could also set into effect auxiliary control measures such as closed areas or time periods. Such a scheme would allow the fishery to be left to its own devices in productive years, while in years of reduced krill availability additional restraints could be exercised.

3. Research and Development

This element can be broadly defined as the conduct, analysis and/or interpretation of studies, which are aimed at reducing measurement uncertainty, monitoring performance of the management scheme, and describing key processes.

CCAMLR should encourage research activities that will lead to improvements in the ecosystem monitoring program and the krill management scheme. Sampling procedures and measurement technologies are constantly improving. In this regard, it is important to separate what process should be monitored from how it is monitored with the goal of reducing measurement uncertainty. New techniques should be calibrated against older methods, but inconsistency should not be a barrier to reducing uncertainty. Monitoring performance of the management scheme may be impossible in the absence of a large fishery on krill, but some criteria will have to be established by which success can be judged. For example, a stable krill population, or stable predator populations, or controlled growth of the fishery may be established by CCAMLR as management objectives and appropriate performance measures developed. These objectives, however, may not be attainable if the system is changing and CCAMLR may have to set different objectives. Ultimately, the value of CCAMLR's management scheme will have to be rationalized and some measure of performance will offer the most credible argument.

As a necessary complement to the CCAMLR Ecosystem Monitoring Program, studies that describe and quantify ecosystem processes should be supported. In addition to research programs undertaken by CCAMLR members, several collaborative research programs have targeted various processes in the Southern Ocean (e.g., JGOFS, AMERIZ, RACER, LTER, SO-GLOBEC), which may provide valuable insights into ocean and atmospheric processes critical to the functioning of the krill-centric ecosystem. These studies should be followed and results examined because they may lead to improvements in the CCAMLR monitoring scheme as well as implications for management decision rules.

Specific processes may also be identified and highlighted for research attention. Examples include:

- **Pelagic production in the spring**. The hypothesized relationships between krill recruitment and the extent of winter sea ice development, the timing of krill spawning, the magnitude of salp population growth and sea ice development in the following winter depend on springtime processes that have never been observed in sufficient detail. The processes of ice retreat, phytoplankton blooms, and secondary production should be studied as they relate to these hypotheses and provide the underlying mechanisms. Is the retreat of sea ice steady or sporadic? Are adult and juvenile krill in better condition after a winter of extensive sea ice development than one with little sea ice? Does the extent of sea ice and/or the rate of its retreat dictate the extent, duration, and species composition of phytoplankton blooms? Do krill and salps compete for phytoplankton in the early spring, and, if so, under what conditions is the competition mitigated? What dictates the character and rate of species succession in both phytoplankton and zooplankton?

- **Regulation of penguin population growth**. Potential variability in reproductive success may not be sufficient to drive observed changes in sea bird population sizes (Russell and Musick, 1999). It has been suggested that survival from fledging to first breeding may be the dominant control on the growth of certain penguin populations (Croxall and Rothery, 1995; Trivelpiece, in prep). A key process may be the ability for first-feeding fledglings to locate adequate food supplies during their first few weeks at sea. This is also the time when their parents are consuming krill in preparation for their molt and the local demand for krill is at its seasonal high (Croll and Tershey, 1998). A critical element in this process may be the timing of offshore krill spawning, the movement onshore of post-spawning adults, and their aggregation into large, relatively stationary swarms. Where do fledglings forage during their first few weeks at sea? What is their survival rate and does it vary in response to changes in krill spawning and availability?

It is our hope that the foregoing outline may stimulate discussion among CCAMLR members toward the development of a strategic plan. A window of opportunity currently exists wherein a scheme of ecosystem monitoring and management may be established while human demand for the krill resource is relatively low. It may never be possible to completely specify the system or to even describe the true variability associated with components of the system. It may be more realistic to identify key processes, develop methods for monitoring those processes, and elaborate a set of management decision rules based on process indicators. Such a scheme would not replace the current krill yield model but rather incorporate and extend it.

V. FINAL COMMENT ON THE VALUE OF A CONSERVATION ETHIC

The ill-fated histories of many other international fishery regimes have resulted in drastic overexploitation and reactive, single species management. In contrast, CCAMLR retains a unique opportunity to establish proactive measures that allow for ecologically sustainable krill harvesting. Although immediate threat of overexploitation of the krill resource appears to be small, pressure from the growing world's population combined with technological advances in krill processing and product development may prompt increased harvest. CCAMLR members recognize the need to update existing krill population estimates and enhance research efforts. Furthermore, the Scientific Committee has emphasized the development of flexible management strategies, particularly those that would allow incorporation of environmental variables and trophic interactions (SC-CAMLR, 1997).

Despite these intentions, obstacles to effective krill management remain. Levels of scientific uncertainty are high and Antarctic research efforts are costly. Although mechanisms for generating scientific advice and those for decision making are for the most part decoupled, advice from the Scientific Committee to the Commission is inevitably rife with uncertainty that, in turn complicates the formulation of conservation priorities and management measures. Moreover, consensus-based management decisions may be difficult to achieve even if knowledge were plentiful. In consensus-based systems with voluntary compliance such as CCAMLR, participants can be expected to agree to only those measures that support their nation's best interests (Vicuna, 1996). Therefore, it may be expected that the political agendas of CCAMLR member nations will influence management actions.

If a lucrative fishery were to arise in response to technological advances, a number of nations interested in promoting a krill industry might alter their conservationist stance. Furthermore, the distinction between fishing members and conservation-minded members in CCAMLR, while clear in the early years, has changed. Fishing companies based in Australia, New Zealand, the UK, and the USA (all considered at one time to be conservation-minded members of CCAMLR) are currently conducting commercial fisheries in waters under CCAMLR jurisdiction. Commissioners to CCAMLR from these nations may find themselves under increasing pressure to appease competing economic interests and political agendas. In addition, interest in fishing for Antarctic krill might be generated in nations that are not members of CCAMLR. Under these circumstances, CCAMLR may try to increase its membership and/or strengthen its ties with other international agreements. In any event, compromise and consolidation of political agendas will be necessary.

The ecosystem approach adopted by CCAMLR requires a large investment in scientific research as well as effective coordination of national scientific efforts. As was the case with the whaling nations in the International Whaling Commission, krill fishing interests could use scientific uncertainty as a reason to oppose additional management measures. Compounding the problem, these interests could hinder the collection or analysis of additional data necessary to rationalize revised precautionary limits for the krill fishery. The remote nature of the fishery might further tendencies of fishing interests to overexploit the krill resource. Fishing companies may be able to escape the costs of overexploitation by leaving for more productive fisheries, and therefore may favor safe profits today rather than an uncertain future.

Given the potential for continued scientific uncertainty and economic pressures to hinder regulation of the krill fishery, what mechanisms might CCAMLR pursue to minimize future conflicts? One option for promoting a consensus on regulative initiatives may lie in the power of individual nations to take a political stand against excessive harvesting, thus increasing pressure on fishing nations and enhancing their own green image. This pressure may be in the form of negative publicity or the imposition of import restrictions and/or trade sanctions under existing agreements. While such actions can sometimes be reasonably opposed on the grounds of inadequate scientific information, arguing against attempts to improve the knowledge base (e.g., additional reporting procedures, the establishment of scientific working groups) is a more difficult position for fishing interests to justify (Joyner, 1992). Promoting information measures may be the best option to enhancing CCAMLR's effectiveness with regard to conservation. If improved knowledge results in less restrictive conservation measures, fishing interests may be compelled to reassess the cost-benefit analysis of large-scale fishing operations.

Ultimately, CCAMLR cannot succeed unless conservation is given the benefit of the doubt in the face of scientific uncertainty. Given the current level of scientific uncertainty and sufficient economic incentives to expand krill fishing, the necessary evidence needed to attain consensus on proactive management measures may not be obtained in time to prevent overharvesting. The converse principle — the traditional precautionary approach — would seem more appropriate: proponents should have to demonstrate that expanded harvest activities would not harm the target species or ecosystem.* CCAMLR members might also adopt a claim to be stewards of krill predators, so that CCAMLR has a stake that can be balanced against the economic interests of fishing proponents. Guided by this ethic, an agreement that scientific uncertainty prevails would support policies of continued restraint, and consensus decision making could indeed enhance rather than hinder the CCAMLR regime. Other-

* Other recent CCAMLR conservation measures have tended to reverse the burden of proof. For example, rather than approving the development of new fisheries "carte blanche," CCAMLR mandates the initial development of restricted "exploratory" or "experimental" fisheries. This requires the fishing nation to take a precautionary approach in the hopes of determining fishery impacts and adequate catch limits prior to substantial economic investment.

wise, pursuit of the consensus-based decision-making system may complicate the ability for managers and scientists from fishing and nonfishing nations to cooperate as scientific uncertainties and economic pressures confound the development of universally acceptable solutions.

Despite these obstacles, the foundation for CCAMLR's ecosystem approach to management of the krill fishery appears to be sound. Member nations, including those with fishery investments, seem willing to cooperate in discussions of management directions and reach a fishery compromise despite economic pressures. Current political pressures provide further incentive to cooperate, as evident by the history of CCAMLR fin-fish management in which some nations agreed to conservation measures not necessarily in their best interest. At least for the time being, all nations appear to agree to the importance of investigating the nature of variability, evaluating krill and predator status objectively, and adjusting management models accordingly. CCAMLR members appear to embrace the ecosystem approach and seem anxious to prove it a success. Challenges to this commitment may be presented by increasing demand for krill and a failure to formally adopt a precautionary policy.

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